Fundamentals Physics

Eleventh Edition

Halliday

Chapter 5

Force and Motion–I

5-1 Newton's First and Second Laws (1 of 20)

Learning Objectives

5.01 Identify that a force is a vector quantity and thus has both magnitude and direction and also components.

5.02 Given two or more forces acting on the same particle, add the forces as vectors to get the net force.

5.03 Identify Newton's first and second laws of motion.

5.04 Identify inertial reference frames.

5-1 Newton's First and Second Laws (2 of 20)

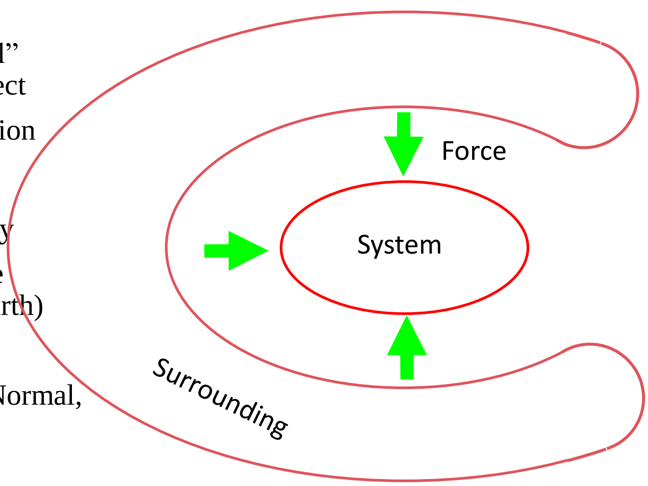
5.05 Sketch a free-body diagram for an object, showing the object as a particle and drawing the forces acting on it as vectors anchored to the particle.

5.06 Apply the relationship between net force on an object, its mass, and the produced acceleration.

5.07 Identify that only external forces on an object can cause the object to accelerate.

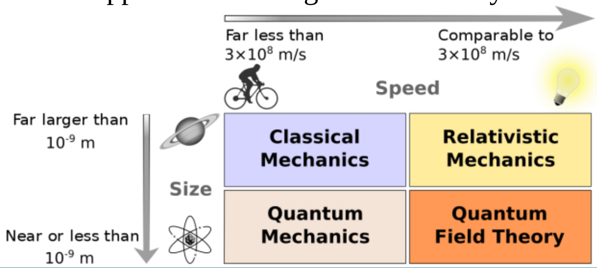
5-1 Newton's First and Second Laws (3 of 20)

- A **force**:
  - Is a "push or pull" acting on an object
  - Causes acceleration
- Law of Forces
  - Universal Gravity
  - Gravity (near the surface of the Earth)
  - Electrostatic
  - Contact Force (Normal, Friction)



5-1 Newton's First and Second Laws (4 of 20)

- We will focus on Newton's three laws of motion:
  - **Newtonian mechanics** is valid for everyday situations
  - It is not valid for speeds which are an appreciable fraction of the speed of light
  - It is not valid for objects on the scale of atomic structure
  - Viewed as an approximation of general relativity



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5-1 Newton's First and Second Laws (5 of 20)

- Before Newtonian mechanics:
  - Some influence (force) was thought necessary to keep a body moving
  - The "natural state" of objects was at rest
- This seems intuitively reasonable (due to friction)
- But envision a **frictionless surface**
  - Does not slow an object
  - The object would keep moving forever at a constant speed
  - Friction is a force!
- **State of motion of an object** : object at rest or moving with constant velocity

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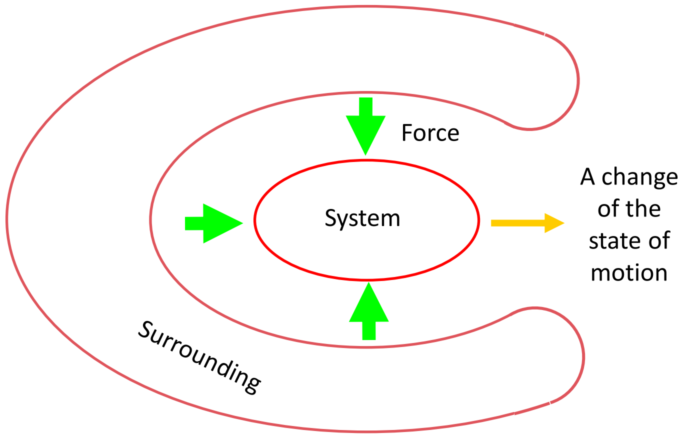
5-1 Newton's First and Second Laws (6 of 20)

Newton's First Law: If no force acts on a body, the body's velocity cannot change: that is, the body cannot accelerate.



5-1 Newton's First and Second Laws (7 of 20)

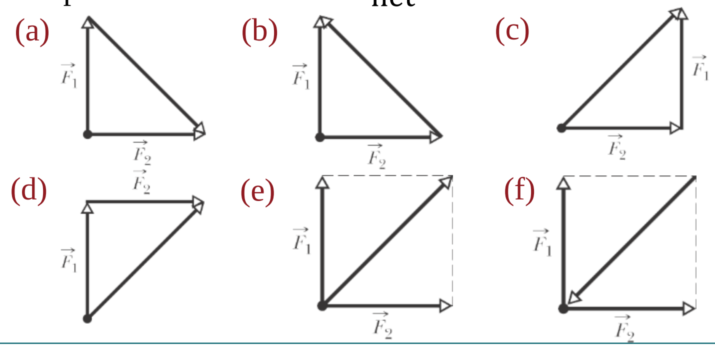
- Characteristics of forces:
    - Unit: N, the newton; $1 \text{ N} = 1 \text{ kg m/s}^2$
    - Acceleration of a mass is proportional to the exerted force
    - Forces are vectors
- **Net force** is the vector sum of all forces on an object
- **Principle of superposition for forces**:
    - A net force has the same impact as a single force with identical magnitude and direction
    - So we can restate more correctly:

Newton's First Law: If no net force acts on a body $(\vec{F}_{\text{net}} = 0)$, the body's **state of motion (inertia) does not change**.

5-1 Newton's First and Second Laws (8 of 20)

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 $\vec{F}_{net}$?



Answer:

(c), (d), (e)

5-1 Newton's First and Second Laws (9 of 20)

- What is mass?
  - "the mass of a body is the characteristic that relates a force on the body to the resulting acceleration"
  - Mass is a measure of a body's resistance to a change in motion (change in velocity)
  - It is not the same as weight, density, size etc.
  - Mass is inversely proportional to acceleration

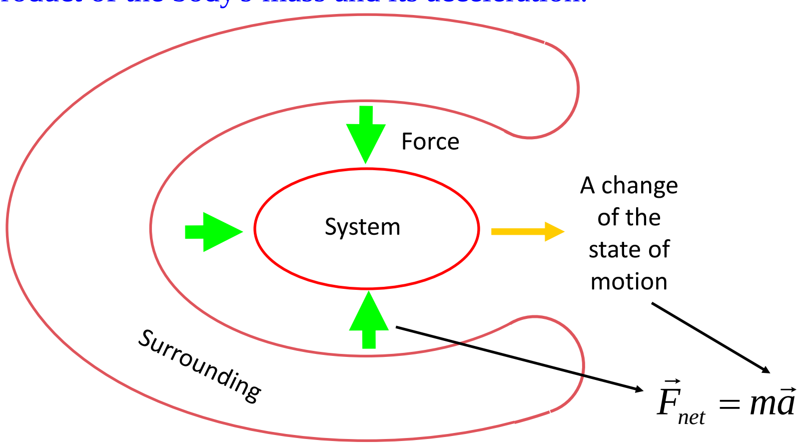
5-1 Newton's First and Second Laws (10 of 20)

Example Apply an 8.0 N force to various bodies:

- Mass: 1kg $\rightarrow$ acceleration: $8\,\text{m/s}^2$
- Mass: 2kg $\rightarrow$ acceleration: 4m/s^2
- Mass: 0.5kg $\rightarrow$ acceleration: 16m/s^2
- Acceleration: 2m/s^2 $\rightarrow$ mass : 4 kg

5-1 Newton's First and Second Laws (11 of 20)

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



5-1 Newton's First and Second Laws (12 of 20)

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

- As an equation, we write:

$$\vec{F}_{\text{net}} = m\vec{a}$$ **Equation (5-1)**

- Identify the body in question, and only include forces that act on that body!
- Separate the problem axes (they are independent):

$$F_{\text{net},x} = ma_x, \quad F_{\text{net},y} = ma_y, \quad \text{and} \quad F_{\text{net},z} = ma_z.$$ **Equation (5-2)**

The acceleration component along a given axis is caused only by the sum of the force components along that same axis, and not by force components along any other axis.

5-1 Newton's First and Second Laws (13 of 20)

- If the net force on a body is zero:
  - Its acceleration is zero
  - The forces and the body are in equilibrium
  - But there may still be forces!
- Units of force:

Table 5-1 Units in Newton's Second Law (Equations. 5-1 and 5-2)

System	Force	Mass	Acceleration
SI	newton (N)	kilogram (kg)	m/s^2
CGS[a]	dyne	gram (g)	cm/s^2
British[b]	pound (lb)	slug	ft/s^2

[a] $1 \text{ dyne} = 1 \text{ g} \cdot \text{cm/s}^2$. [b] $1 \text{ lb} = 1 \text{ slug} \cdot \text{ft/s}^2$.

5-1 Newton's First and Second Laws (14 of 20)

- Newton's first law is not true in all frames
- **Inertial frames**:

  An inertial reference frame is one in which Newton's laws hold.

  (a): a frictionless puck, pushed from the north pole, viewed from space

  (b): the same situation, viewed from the ground
- Over long distances, the ground is a **noninertial frame**
- In (b), a fictitious force would be needed to explain deflection

Newton's First Law: In an **inertial reference frame**, if no net force acts on a body $(\vec{F}_{\text{net}} = 0)$, the body's **state of motion (inertia) does not change**.

5-1 Newton's First and Second Laws (15 of 20)

- Generally, assume the ground is an inertial frame

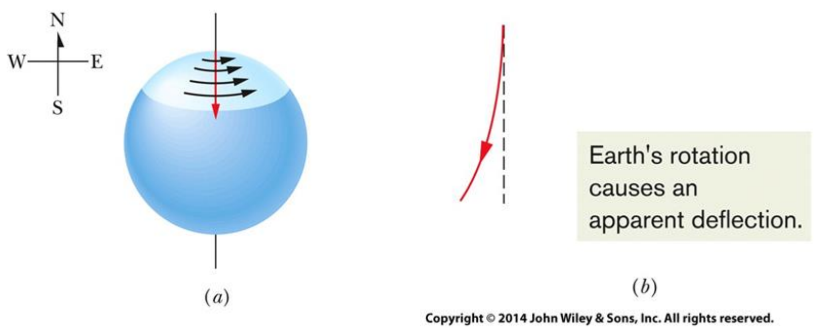


Figure 5-2

5-1 Newton's First and Second Laws (16 of 20)

- To solve problems with forces, we often draw a **free body diagram**
- The only body shown is the one we are solving for
- Forces are drawn as vector arrows with their tails on the body
- Coordinate system shown
- Acceleration is Never part of a free body diagram – only forces on a body are present.

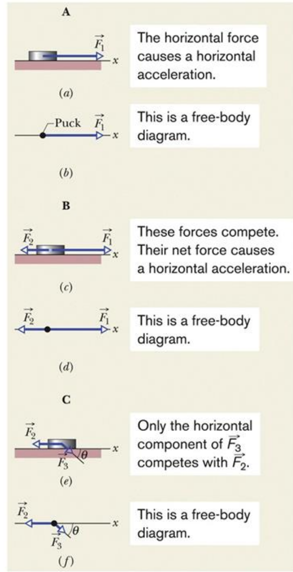
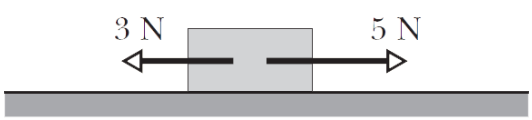


Figure 5-3

5-1 Newton's First and Second Laws (17 of 20)



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?

Answer: F_3 = 2 N to the left in both cases

5-1 Newton's First and Second Laws (18 of 20)

- A **system** consists of one or more bodies
- Any force on the bodies inside a system exerted by bodies outside the system is an **external force**
- Net force on a system = sum of external forces
- Forces between bodies in a system: **internal forces**
  - Not included in a FBD of the system since internal forces cannot accelerate the system

Note: do not confuse a free body diagram of an entire system with free body diagrams of individual bodies within a system.

5-1 Newton's First and Second Laws (19 of 20)

Two-dimensional forces, cookie tin

In the overhead view of Fig. 5-4*a*, a 2.0 kg cookie tin is accelerated at 3.0 m/s² 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 N and $\vec{F}_2$ of magnitude 20 N. What is the third force $\vec{F}_3$ in unit-vector notation and in magnitude-angle notation?

KEY IDEA

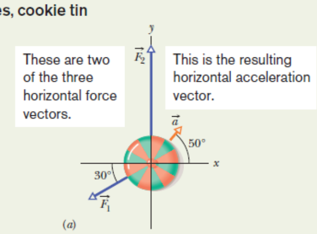
The net force $\vec{F}_{net}$ on the tin is the sum of the three forces and is related to the acceleration $\vec{a}$ via Newton's second law ($\vec{F}_{net} = m\vec{a}$). Thus,

$$\vec{F}_1 + \vec{F}_2 + \vec{F}_3 = m\vec{a}, \quad (5\text{-}6)$$

which gives us

$$\vec{F}_3 = m\vec{a} - \vec{F}_1 - \vec{F}_2. \quad (5\text{-}7)$$

Calculations: Because this is a two-dimensional problem, we *cannot* find $\vec{F}_3$ merely by substituting the magnitudes for the vector quantities on the right side of Eq. 5-7. Instead, we must vectorially add $m\vec{a}$, $-\vec{F}_1$ (the reverse of $\vec{F}_1$), and $-\vec{F}_2$ (the reverse of $\vec{F}_2$), as shown in Fig. 5-4*b*. This addition can be done directly on a vector-capable calculator because we know both magnitude and angle for all three vectors. However, here we shall evaluate the right side of Eq. 5-7 in terms of components, first along the *x* axis and then along the *y* axis.



(*a*)

x components: Along the *x* axis we have

$$F_{3,x} = ma_x - F_{1,x} - F_{2,x}$$
$$= m(a\cos 50°) - F_1\cos(-150°) - F_2\cos 90°.$$

Then, substituting known data, we find

$$F_{3,x} = (2.0\text{ kg})(3.0\text{ m/s}^2)\cos 50° - (10\text{ N})\cos(-150°) - (20\text{ N})\cos 90°$$
$$= 12.5\text{ N}.$$

y components: Similarly, along the *y* axis we find

$$F_{3,y} = ma_y - F_{1,y} - F_{2,y}$$
$$= m(a\sin 50°) - F_1\sin(-150°) - F_2\sin 90°$$
$$= (2.0\text{ kg})(3.0\text{ m/s}^2)\sin 50° - (10\text{ N})\sin(-150°) - (20\text{ N})\sin 90°$$
$$= -10.4\text{ N}.$$

5-1 Newton's First and Second Laws (20 of 20)

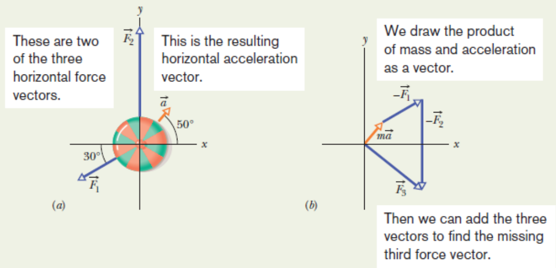


Fig. 5-4 (*a*) An overhead view of two of three horizontal forces that act on a cookie tin, resulting in acceleration $\vec{a}$. $\vec{F}_3$ is not shown. (*b*) An arrangement of vectors $m\vec{a}$, $-\vec{F}_1$, and $-\vec{F}_2$ to find force $\vec{F}_3$.

Vector: In unit-vector notation, we can write

$$\vec{F}_3 = F_{3,x}\hat{\mathrm{i}} + F_{3,y}\hat{\mathrm{j}} = (12.5\ \mathrm{N})\hat{\mathrm{i}} - (10.4\ \mathrm{N})\hat{\mathrm{j}}$$
$$\approx (13\ \mathrm{N})\hat{\mathrm{i}} - (10\ \mathrm{N})\hat{\mathrm{j}}. \qquad \text{(Answer)}$$

We can now use a vector-capable calculator to get the magnitude and the angle of $\vec{F}_3$. We can also use Eq. 3-6 to obtain the magnitude and the angle (from the positive direction of the x axis) as

$$F_3 = \sqrt{F_{3,x}^2 + F_{3,y}^2} = 16\ \mathrm{N}$$

and

$$\theta = \tan^{-1}\frac{F_{3,y}}{F_{3,x}} = -40^\circ. \qquad \text{(Answer)}$$

5-2 Some Particular Forces (1 of 15)

Learning Objectives

5.08 Determine the magnitude and direction of gravitational force on a mass, for a given free-fall acceleration.

5.09 Identify that weight is the magnitude of the net force required to prevent a body from falling freely, measured by the frame of ground.

5.10 Identify that a scale gives an object’s weight when the measurement is done in an inertial frame but not in an accelerating frame, where it gives an apparent weight.

5-2 Some Particular Forces (2 of 15)

5.11 Determine the magnitude and direction of the normal force on an object when the object is pressed or pulled onto a surface.

5.12 Identify that the force parallel to the surface is a frictional force that appears when the object slides or attempts to slide.

5.13 Identify that a tension force is said to pull at both ends of a cord (or a cord-like object) when the cord is taut.

5-2 Some Particular Forces (3 of 15)

- The **gravitational force**:
  - A pull that acts on a body, directed toward a second body
  - Generally we consider situations where the second body is Earth
- In free fall (*y* direction, with no drag from the air):

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

$$F_g = mg. \qquad \textbf{Equation (5-8)}$$

- This force still acts on a body at rest!
- We can write it as a vector:

$$\vec{F}_g = -F_g\hat{\jmath} = -mg\hat{\jmath} = m\vec{g}, \qquad \textbf{Equation (5-9)}$$

5-2 Some Particular Forces (4 of 15)

Weight:

- The name given to the gravitational force that one body (like the Earth) exerts on an object
  - It is a force measured in newtons (N)
  - It is directed downward towards the center

$$W = F_g \quad (\text{weight, with ground as inertial frame}).$$

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

5-2 Some Particular Forces (5 of 15)

Example To relate weight to mass, consider an apple in free fall. The only force on the apple is the gravitational force which results in an acceleration of g. Applying Newton's 2nd Law

$$F_{\text{net}} = ma \quad \text{where } F_{\text{net}} = F_g = W \text{ and } a = g$$

$$F_g = W = mg$$

Thus,

$$W = mg \quad (\text{mass} - \text{weight relationship})$$

5-2 Some Particular Forces (6 of 15)

- Measuring weight:
  - Use a balance to compare a body to known masses, find its mass, and compute its weight
  - Use a spring scale that measures weight on a calibrated scale
  - Weight is not the same as mass: a pan balance will read the same for different values of *g*, a scale will read differently for different values of *g*
- Weight must be measured when the body is not accelerating vertically
  - E.g., in your bathroom, or on a train
  - But not in an elevator

5-2 Some Particular Forces (7 of 15)

- The **normal force:**
  - If you are standing on a surface, the push back on you from the surface (due to deformation) is the normal force
  - Normal means perpendicular

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

5-2 Some Particular Forces (8 of 15)

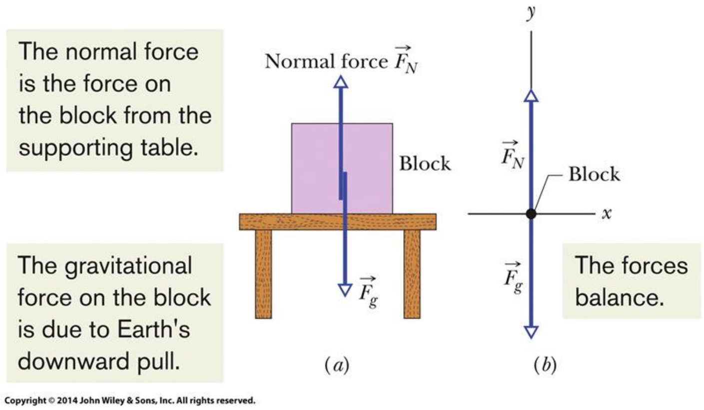


Figure 5-7

5-2 Some Particular Forces (9 of 15)

Example Normal force for a block resting on a horizontal surface that is:

- Accelerating vertically at a_y:

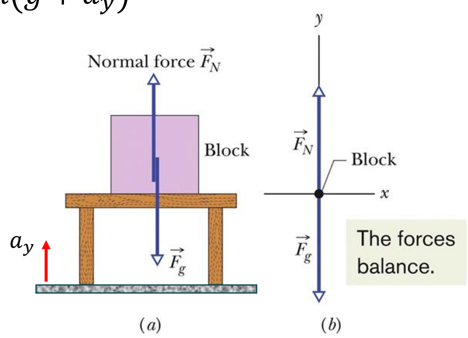
  $$F_N - mg = ma_y \rightarrow F_N = m(g + a_y)$$

  Equation (5-13)

- Vertically at rest:

  $$F_N - mg = 0 \rightarrow F_N = mg$$

  Equation (5-14)



5-2 Some Particular Forces (10 of 15)

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?

Answer:

(a) equal to *mg* (no acceleration)

(b) greater than *mg* (see 5-13, with positive acceleration)

5-2 Some Particular Forces (11 of 15)

- **Frictional force** or **friction**:
  - Occurs when one object slides or attempts to slide over another
  - Directed along the surface, opposite to the direction of intended motion

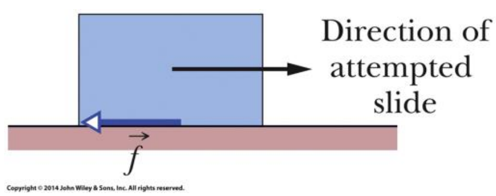


Figure 5-8

5-2 Some Particular Forces (12 of 15)

- **Tension force:**
  - A cord (or rope, etc.) is attached to a body and pulled taut
  - Cord pulls on the body with force T directed along the cord
  - The cord is said to be under tension
  - The tension in the cord is T
- A massless and unstretchable cord exists only as a connection between two bodies
  - It pulls on both with the same force, T
  - True even if the bodies and cord are accelerating, and even if the cord runs around a massless, frictionless pulley
  - These are useful simplifying assumptions

5-2 Some Particular Forces (13 of 15)

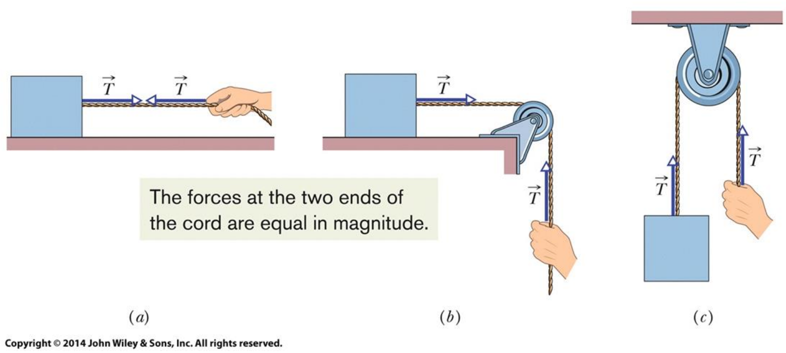
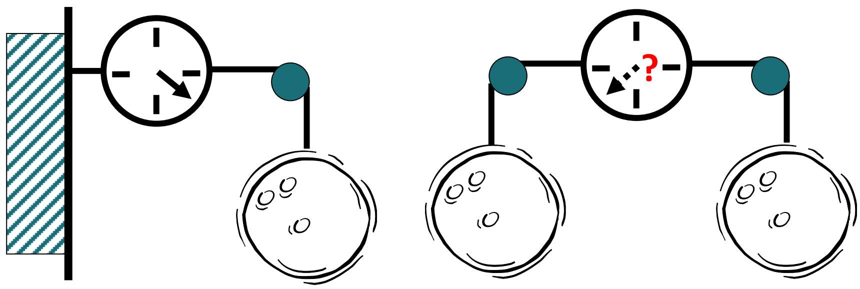


Figure 5-9

5-2 Some Particular Forces (14 of 15)

A 6 kg bowling ball is hung from a rope attached to a scale which is attached to a wall. The scale reads 6 kg.
It is now attached to another bowling ball. What does it read?

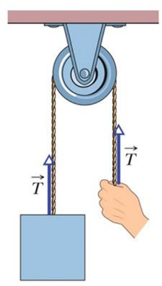


A) 0 B) 6 kg C) 12 kg

5-2 Some Particular Forces (15 of 15)

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?



(*c*)

Answer:

(a) equal to 75 N

(b) greater than 75 N

(c) less than 75 N

5 Summary (1 of 4)

Newtonian Mechanics

- Forces are pushes or pulls
- Forces cause acceleration

Force

- Vector quantities
- $1\ \text{N} = 1\ \text{kg m/s}^2$
- Net force is the sum of all forces on a body

5 Summary (2 of 4)

Newton's First Law

- If there is no net force on a body, the body remains at rest if it is initially at rest, or moves in a straight line at constant speed if it is in motion.

Inertial Reference Frames

- Frames in which Newtonian mechanics holds

5 Summary (3 of 4)

Mass

- The characteristic that relates the body's acceleration to the net force
- Scalar quantity

Newton's Second Law

$$\vec{F}_{\text{net}} = m\vec{a}$$ **Equation (5-1)**

- Free-body diagram represents the forces on one object

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5 Summary (4 of 4)

Some Particular Forces

- Weight:

$$W = mg$$ **Equation (5-12)**

- Normal force from a surface
- Friction along a surface
- Tension in a cord

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