PHYS121 Integrated Science-Physics

W1T4 Force, Newton's laws of motion and applications

References:
[1] David Halliday, Jearl Walker, Resnick Jearl, 'Fundamentals of Physics', (Wiley, 2018)
[2] Doug Giancoli, 'Physics for Scientists and Engineers with modern physics', (Pearson, 2009)
[3] Hugh D. Young, Roger A. Freedman, 'University Physics with Modern Physics', (Pearson, 2012)
And others specified when needed.

昆山杜克大学
DUKE KUNSHAN UNIVERSITY

4.4.1. Complete the following statement: In two-dimensional motion in the *x*-*y* plane, the *x* part of the motion and the *y* part of the motion are independent

a) only if there is no acceleration in either direction.

b) only if there is no acceleration in one of the directions.

c) only if there is an acceleration in both directions.

d) whether or not there is an acceleration in any direction.

e) whenever the acceleration is in the *y* direction only.

Learning outcomes

- Explain the concept of force.
- Describe main characteristics of some typical forces, e.g., gravity, normal force, friction, tension.
- Explain Newton's laws of motion and inertial reference frame.
- Solve problems using Newton's laws of motion.

Force

- A **force**: (some kind of interaction)
  - Is a "push or pull/attract or repel" acting on an object
  - Causes acceleration
- 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

Slide based on Ref. [1]

- 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
- Before Newtonian mechanics:
  - Some influence (force) was thought necessary to keep a body moving
  - The "natural state" of objects was at rest

Newton's First Law

Newton's First Law: If no net force acts on a body $\left(\vec{F}_{\text{net}} = 0\right)$, the body's velocity cannot change; that is, the body cannot accelerate (at rest of uniform velocity in a straight line).

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

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

- Generally, assume the ground is an inertial frame

Slide based on Ref. [1]

Mass

- What is mass?
  - “the mass of a body is the characteristic that relates a force on the body to the resulting acceleration” (inertial mass)
  - 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 (condition)*

Newton’s Second Laws

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.

Free body diagram (FBD)

- 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.

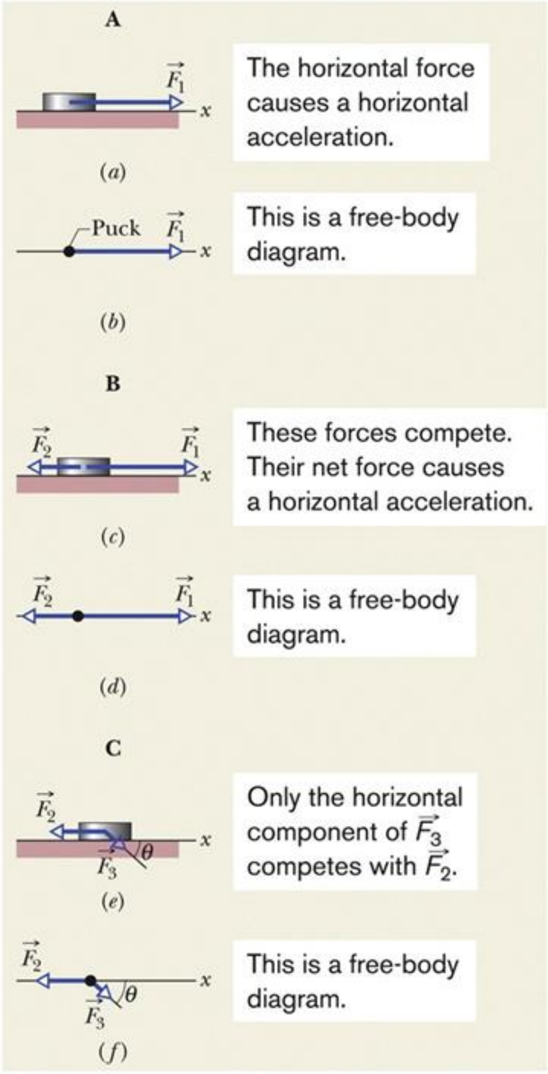
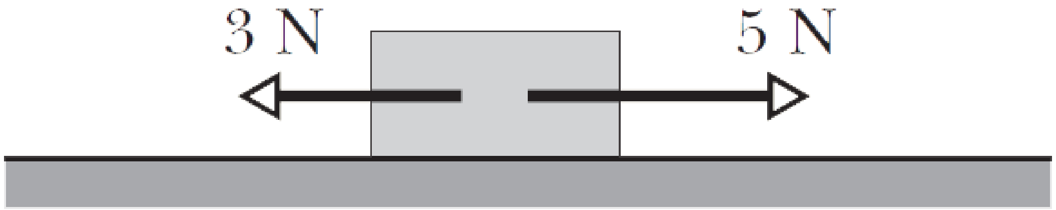


Figure 5-3



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

‘A system’

- 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 (cancel out)

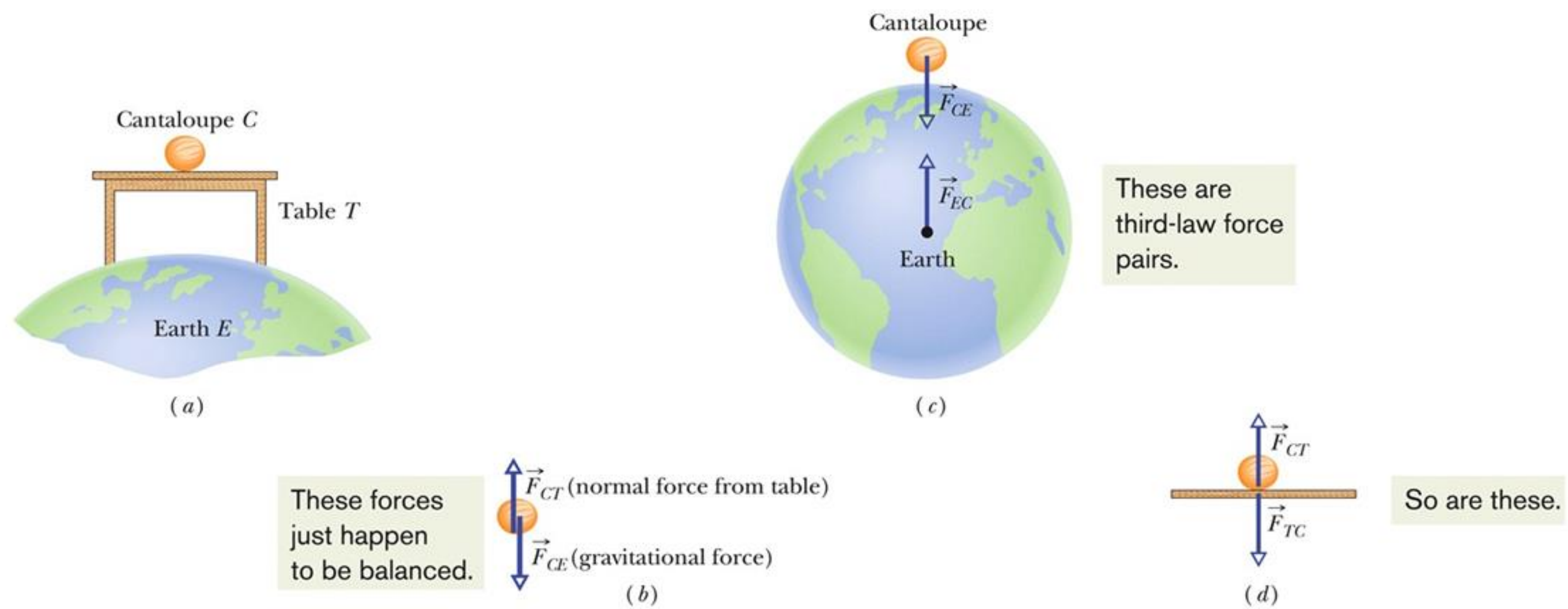
Note: do not confuse a free body diagram of an entire system with free body diagrams of individual bodies within a system.

Newton’s Third Law of Motion

Any time a force is exerted on an object, that force is caused by another object.

Newton’s third law:

Whenever one object exerts a force on a second object, the second exerts an equal force in the opposite direction on the first.



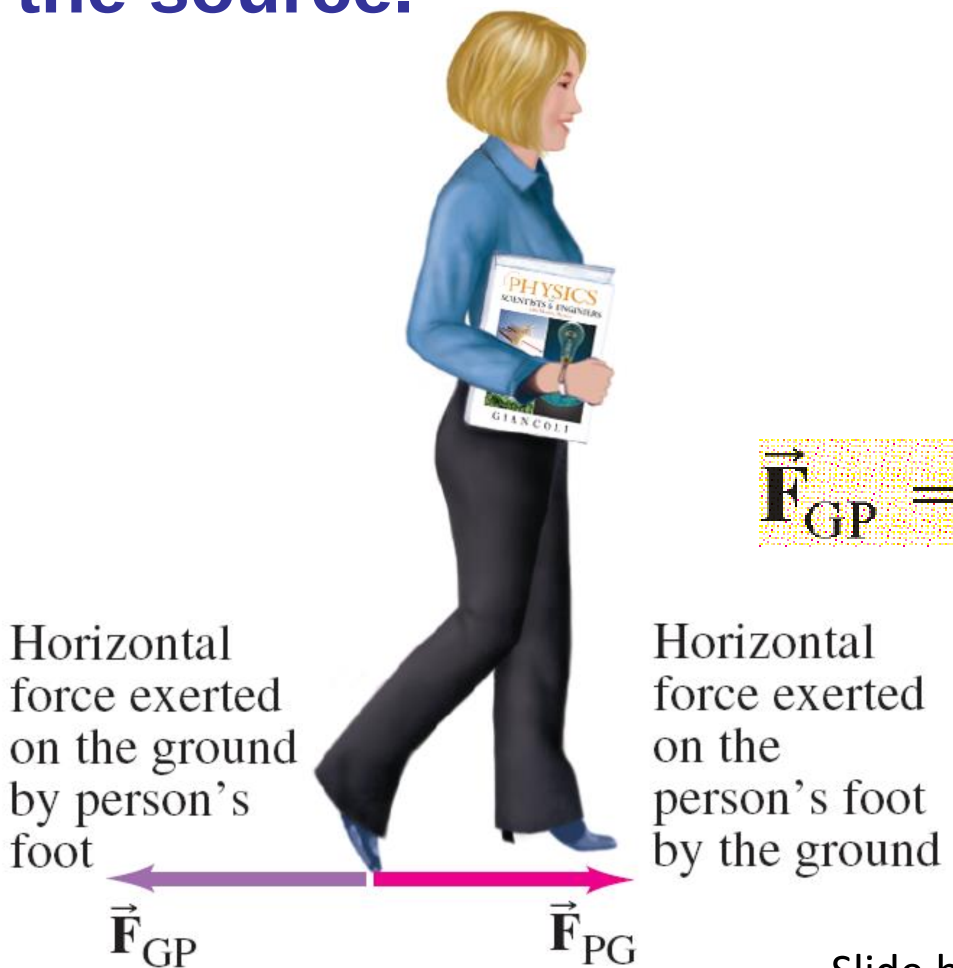
Picture from Ref. [1]

Figure 5-11

Slide based on Ref. [2]

Newton's Third Law of Motion

Helpful notation: the first subscript 脚标 is the object that the force is being exerted on; the second is the source.



$$\vec{F}_{GP} = -\vec{F}_{PG}$$

Slide based on Ref. [2]

Gravitational force (gravity)

- 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, near the surface of Earth):

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

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

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

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

Weight

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

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

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

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

- 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

Normal force

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.

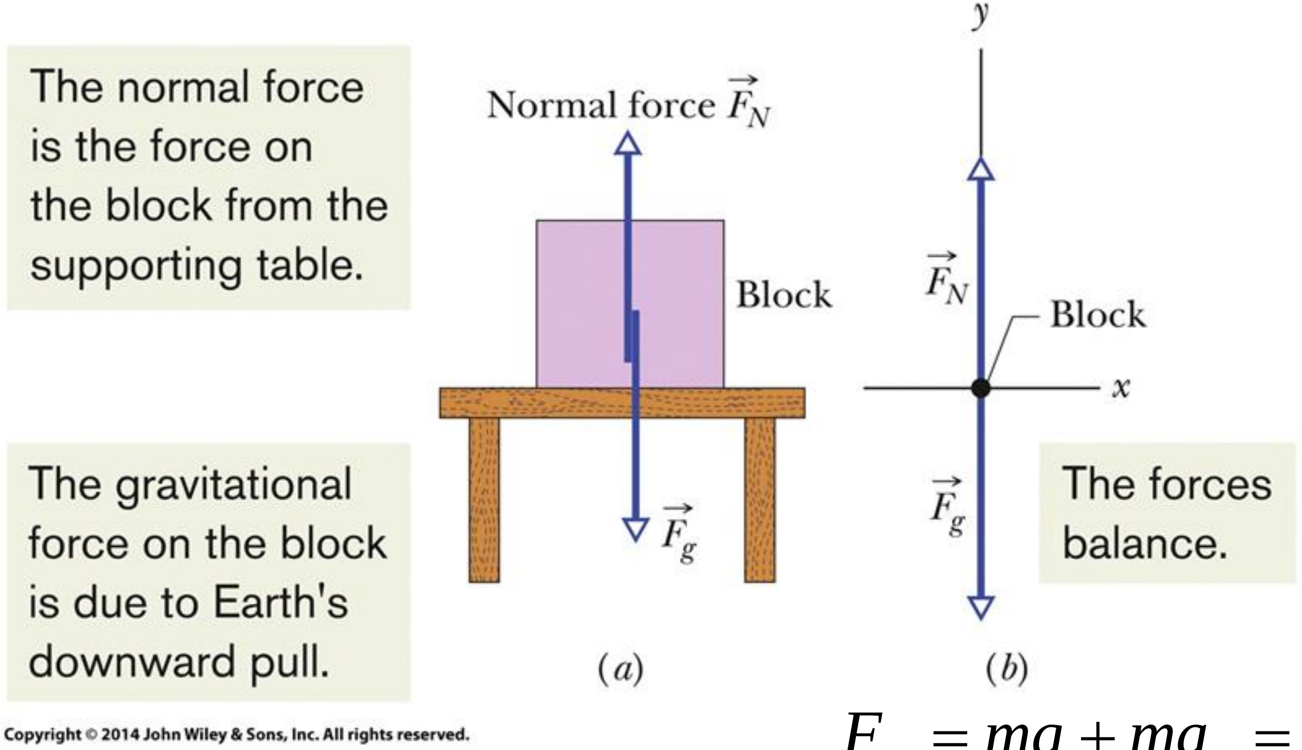


Figure 5-7

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

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

Friction

- **Frictional force** or **friction**: (more details in next chapter)
  - Occurs when one object *slides or attempts to slide* over another
  - *Directed along the surface, opposite to the direction of intended motion*

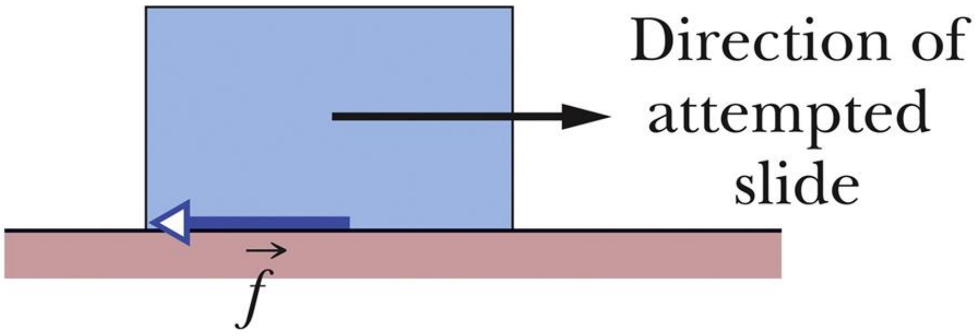


Figure 5-8

CANADA SCIENCE AND TECHNOLOGY MUSEUM

MUSÉE DES SCIENCES ET DE LA TECHNOLOGIE DU CANADA

https://www.youtube.com/watch?v=2StJV-jHU6A

Tension force

- **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

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?

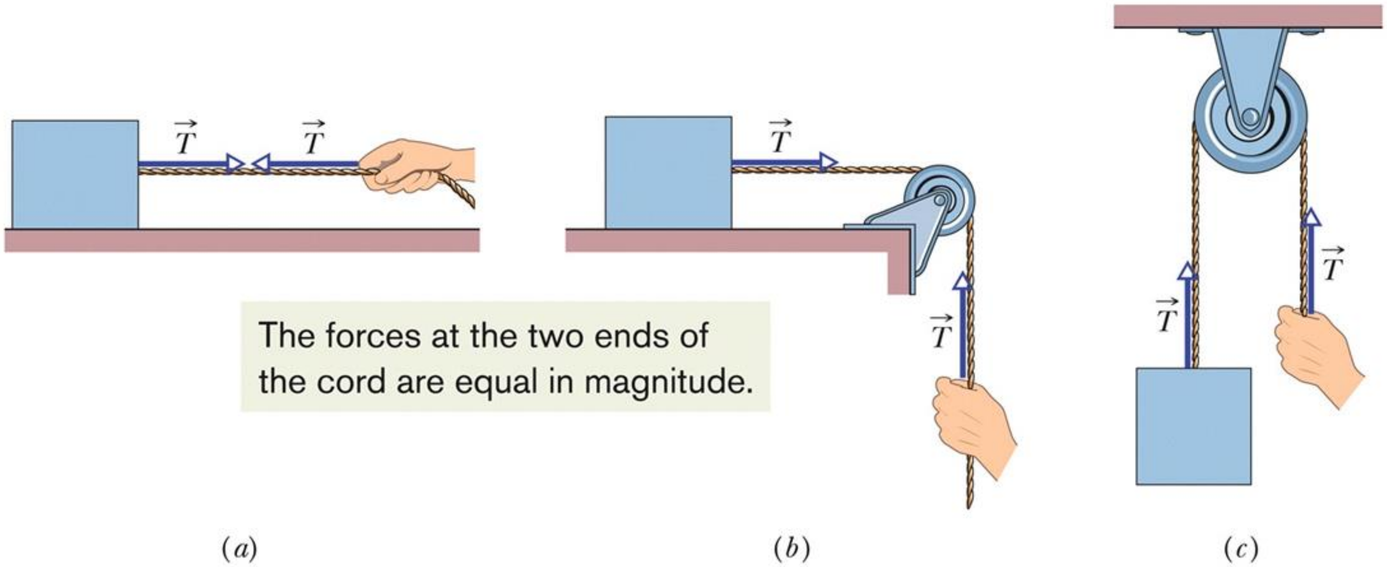


Figure 5-9

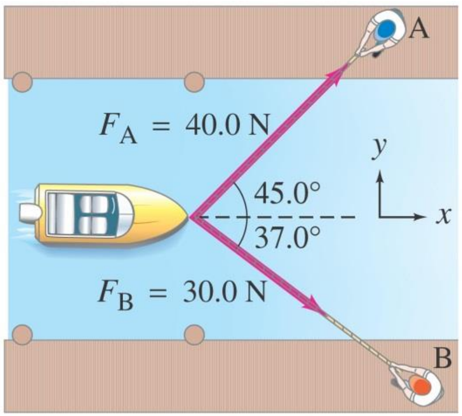
Answer:

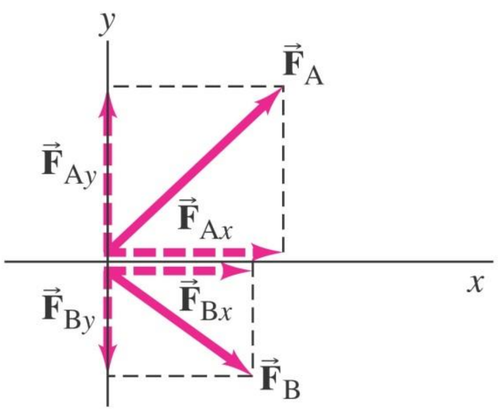
(a) equal to 75 N

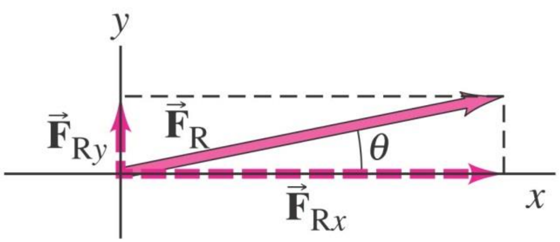
(b) greater than 75 N

(c) less than 75 N

Solving Problems with Newton's Laws: Free-Body Diagrams







1. Draw a **sketch**.
2. For one object, draw a **free-body diagram** 受力分析图, showing all the forces acting *on* the object. Make the **magnitudes** and **directions** as accurate as you can. **Label** each force. If there are multiple objects, draw a separate diagram for each one.
3. **Resolve** vectors into components.
4. Apply Newton's **second law** to each component.
5. Solve.

Slide based on Ref. [2]

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?

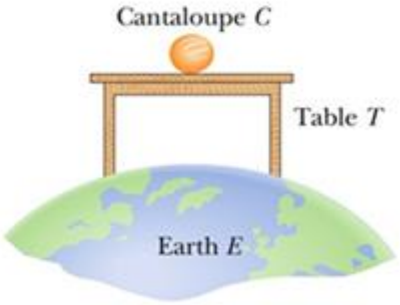
Answer:

(a) they increase

(b) yes

(c) they begin to decrease slowly (the gravitational force of Earth decreases with height—negligible in an actual elevator)

(d) yes



(a)

Sample Problem A block of mass $M = 3.3$ kg, connected by a cord and pulley to a hanging block of mass $m = 2.1$ kg, slides across a *frictionless* surface.

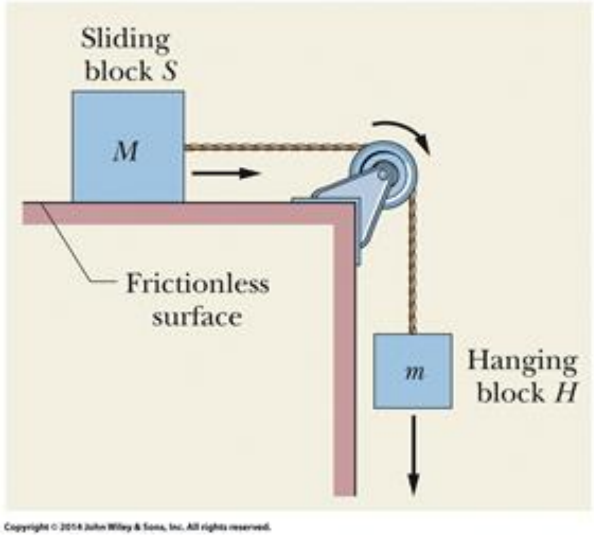


Figure 5-12

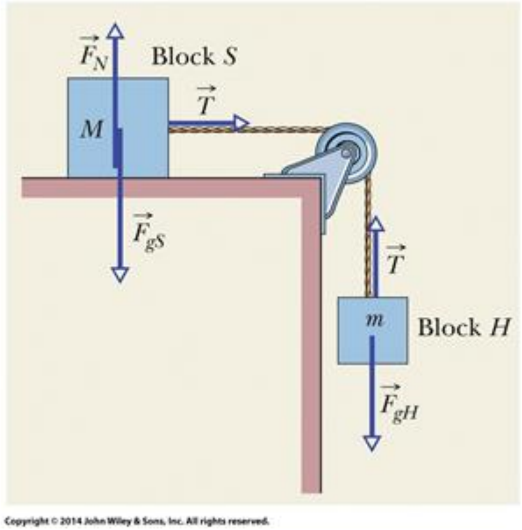


Figure 5-13

Find (a) the acceleration of block S, (b) the acceleration of block H, and (c) the tension in the cord.

- Draw the forces involved
- Treat the string as *unstretchable*, the pulley as massless and frictionless, and each block as a particle
- Draw a free-body diagram for each mass
- Apply Newton's 2nd law ($F = ma$) to each block $\rightarrow$ 2 simultaneous equations.
- Eliminate unknowns (T) that are the same, and solve for the acceleration

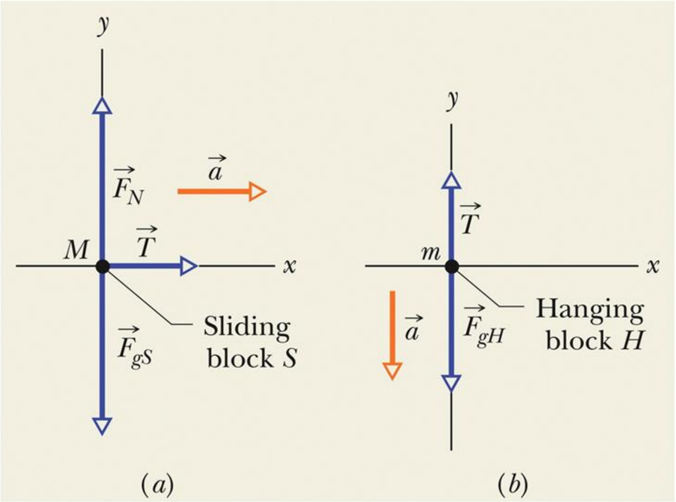


Figure 5-14

Applying Newton's Laws

- For the sliding block: $T = Ma.$ **Equation (5-18)**
- For the hanging block: $T - mg = -ma.$ **Equation (5-20)**
- Combining we get:

$$a = \frac{m}{M+m}g. \quad \textbf{Equation (5-21)} \qquad T = \frac{Mm}{M+m}g. \quad \textbf{Equation (5-22)}$$

- Plugging in we find $a = 3.8\ \text{m/s}^2$ and $T = 13\ \text{N}$
- Does this make sense? Check that dimensions are correct, check that $a < g$, check that $T < mg$ (otherwise acceleration would be upward), check limiting cases $\left(\text{e.g.},\ g = 0,\ M = 0,\ m = \infty\right)$

Sample Problem A block being pulled up a ramp:

Figure 5-15 (*a*) A box is pulled up a plane by a cord. (*b*) The three forces acting on the box: the cord's force $\vec{T}$, the gravitational force $\vec{F}_g$, and the normal force $\vec{F}_N$. (*c*)–(*i*) Finding the force components along the plane and perpendicular to it.

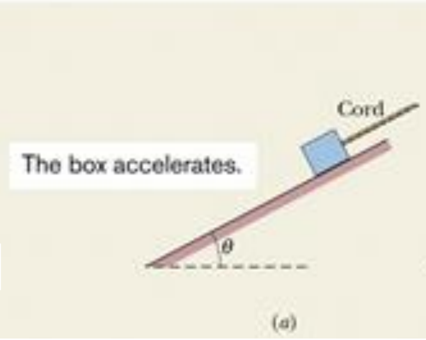


Figure 5-15

Learning outcomes

- ✓ Explain the concept of force.
- ✓ Describe main characteristics of some typical forces, e.g., gravity, normal force, friction, tension.
- ✓ Explain Newton's laws of motion and inertial reference frame.
- ✓ Solve problems using Newton's laws of motion.

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

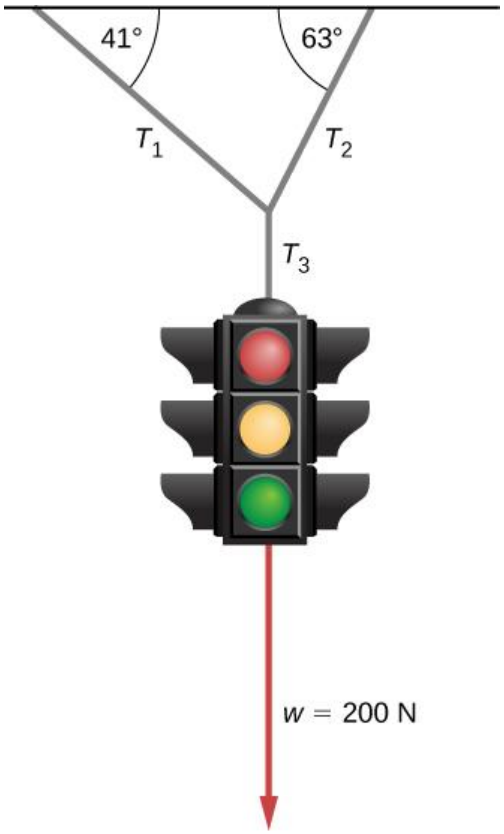
Newton’s first law is general and can be applied to anything from an object sliding on a table to a satellite in orbit to blood pumped from the heart. Experiments have verified that any change in velocity (speed or direction) must be caused by an external force. The idea of *generally applicable or universal laws* is important—it is a basic feature of all laws of physics. Identifying these laws is like recognizing patterns in nature from which further patterns can be discovered. The genius of Galileo, who first developed the idea for the first law of motion, and Newton, who clarified it, was to ask the fundamental question: “What is the cause?” Thinking in terms of cause and effect is fundamentally different from the typical ancient Greek approach, when questions such as “Why does a tiger have stripes?” would have been answered in Aristotelian fashion, such as “That is the nature of the beast.” The ability to think in terms of cause and effect is the ability to make a connection between an observed behavior and the surrounding world.

https://openstax.org/books/university-physics-volume-1/pages/5-2-newtons-first-law

CHAPTER REVIEW AND EXAMPLES, DEMOS

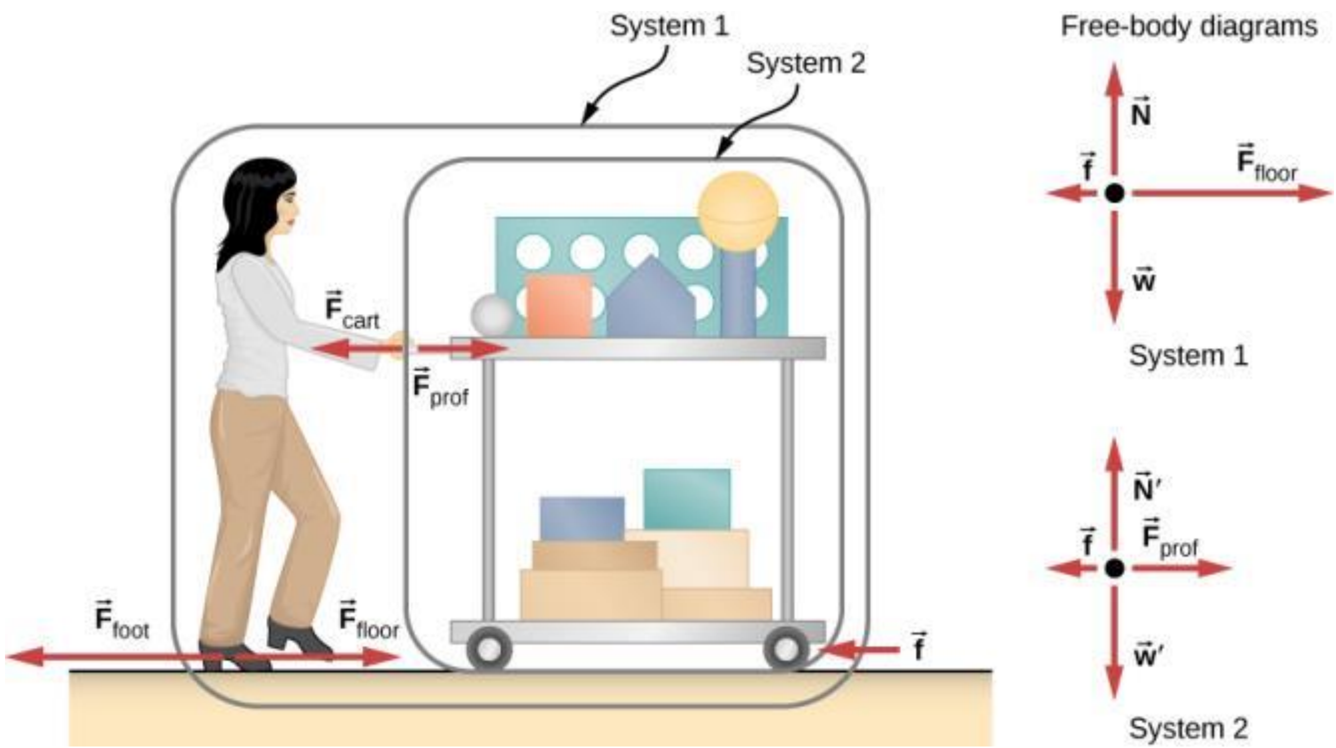
https://openstax.org/books/university-physics-volume-1/pages/5-summary

Analyze the forces involved.



EXERCISE 71

FIGURE 5.20



A professor pushes the cart with her demonstration equipment. The lengths of the arrows are proportional to the magnitudes of the forces (except for $\vec{\mathbf{f}}$, because it is too small to drawn to scale). System 1 is appropriate for this example, because it asks for the acceleration of the entire group of objects. Only $\vec{\mathbf{F}}_{\text{floor}}$ and $\vec{\mathbf{f}}$ are external forces acting on System 1 along the line of motion. All other forces either cancel or act on the outside world. System 2 is chosen for the next example so that $\vec{\mathbf{F}}_{\text{prof}}$ is an external force and enters into Newton’s second law. The free-body diagrams, which serve as the basis for Newton’s second law, vary with the system chosen.

FIGURE 5.30

Hurricane Fran is shown heading toward the southeastern coast of the United States in September 1996. Notice the characteristic “eye” shape of the hurricane. This is a result of the Coriolis effect, which is the deflection of objects (in this case, air) when considered in a rotating frame of reference, like the spin of Earth.

Questions