Chapter 5

Force and Motion–I

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5-1 Newton's First and Second Laws

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.

5.05 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

- A **force**:
  - Is a “push or pull” 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
  - Viewed as an approximation of general relativity

5-1 Newton's First and Second Laws

- 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!

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

- Characteristics of forces:
  - Unit: N, the newton; 1 N = 1 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 ($\vec{F}_{net} = 0$), the body's velocity cannot change; that is, the body cannot accelerate.

5-1 Newton's First and Second Laws

- 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

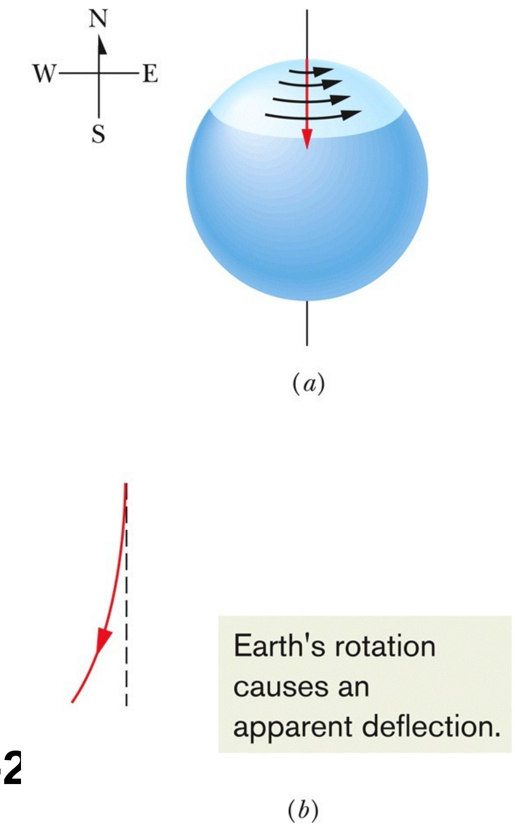


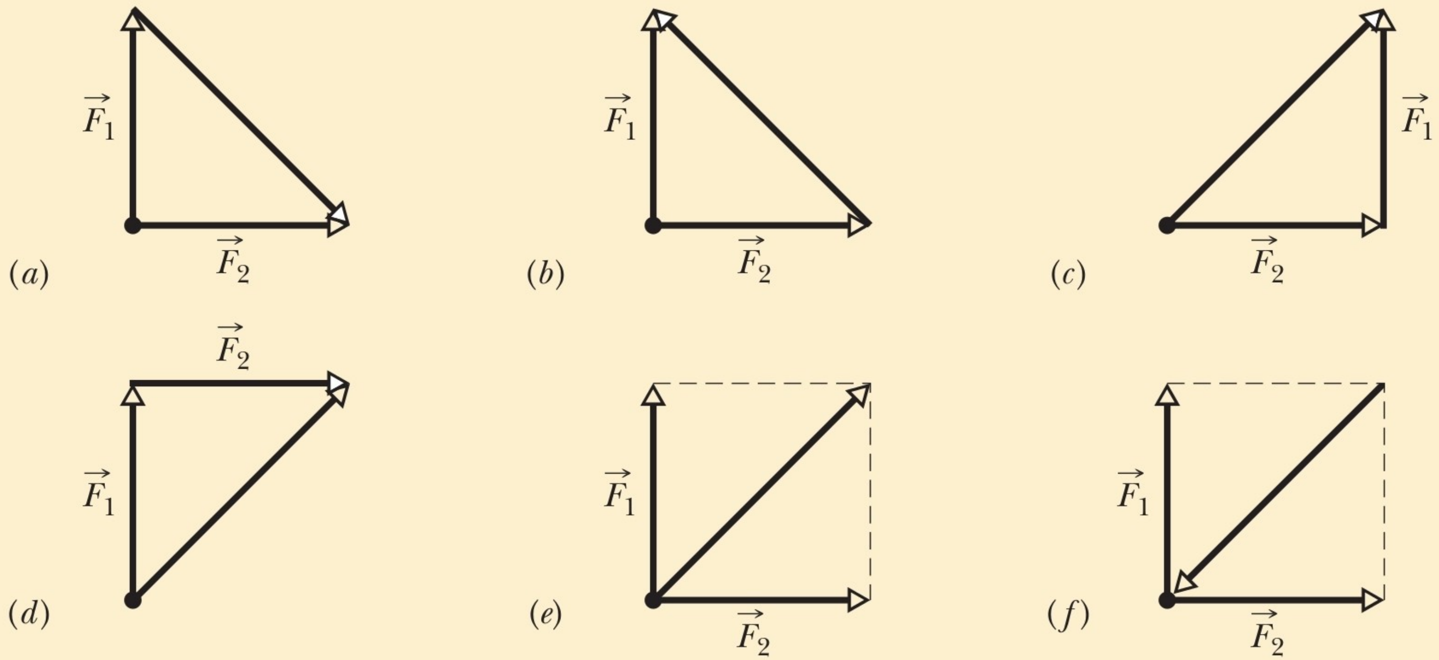
Figure 5-2

5-1 Newton's First and Second Laws

- Generally, assume the ground is an inertial frame

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

- 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

Example Apply an 8.0 N force to various bodies:

- Mass: 1kg → acceleration: 8 m/s^2
- Mass: 2kg → acceleration: 4 m/s^2
- Mass: 0.5kg → acceleration: 16 m/s^2
- Acceleration: 2 m/s^2 → mass: 4 kg

5-1 Newton's First and Second Laws

- Summarize these behaviors as:

> **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:

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

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

$$F_{\text{net},x} = ma_x, \quad F_{\text{net},y} = ma_y, \quad \text{and} \quad F_{\text{net},z} = ma_z.$$ **Eq. (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

- 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 (Eqs. 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] $1\ \text{dyne} = 1\ g \cdot cm/s^2$.

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

Tab. (5-1)

5-1 Newton's First and Second Laws

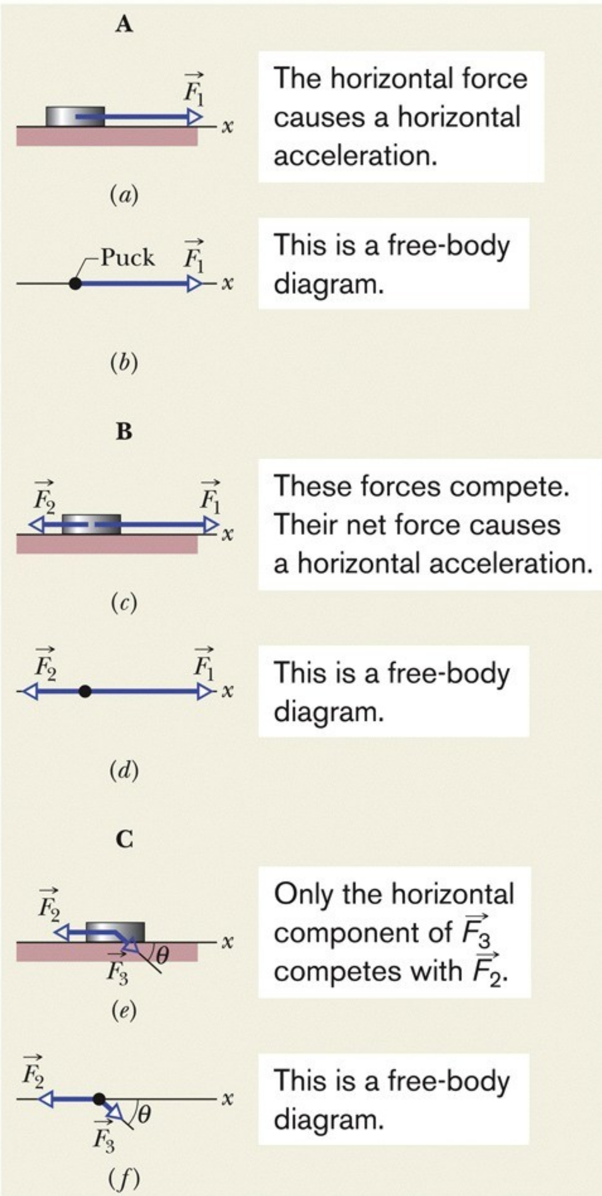


Figure 5-3

- 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.

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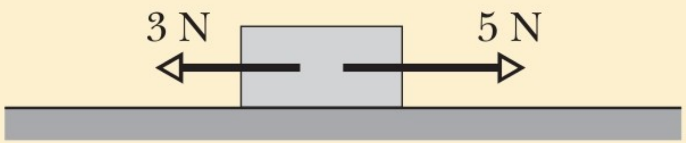
Checkpoint 2



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

- 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.

5-2 Some Particular Forces

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.

5.11 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

- 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):

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

$$F_g = mg.$$

Eq. (5-8)

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

$$\vec{F}_g = -F_g\hat{j} = -mg\hat{j} = m\vec{g},$$

Eq. (5-9)

5-2 Some Particular Forces

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

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

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

Eq. (5-12)

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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

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

$$F_g = W = mg$$

Thus,

$$W = mg$$ (mass – weight relationship)

5-2 Some Particular Forces

- 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

- 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.

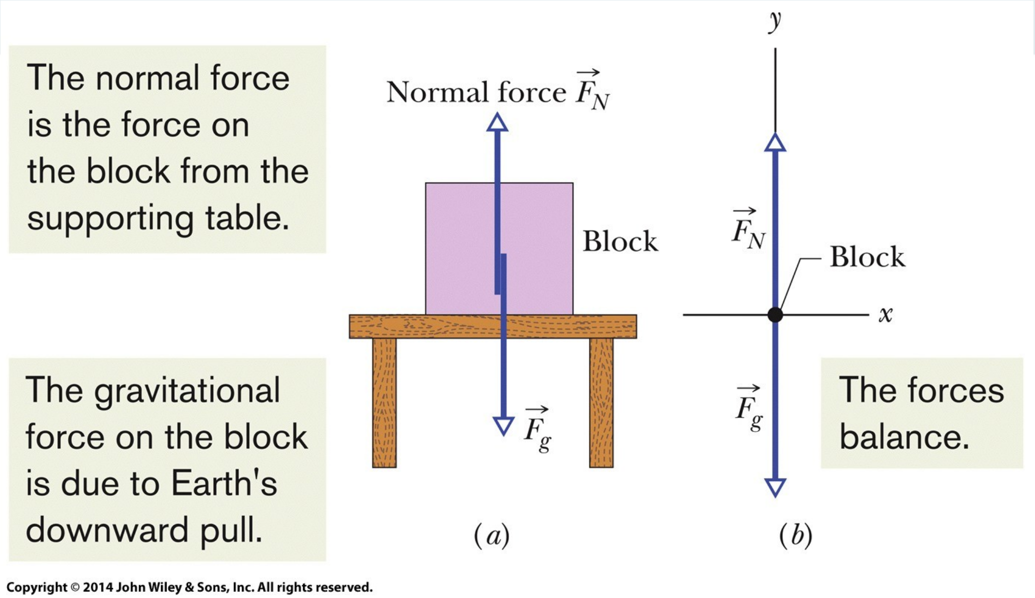

Figure 5-7

5-2 Some Particular Forces

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

- Accelerating vertically at a_y: $$F_N = mg + ma_y = m(g + a_y)$$ **Eq. (5-13)**
- Vertically at rest: $$F_N = mg.$$ **Eq. (5-14)**

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

- **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

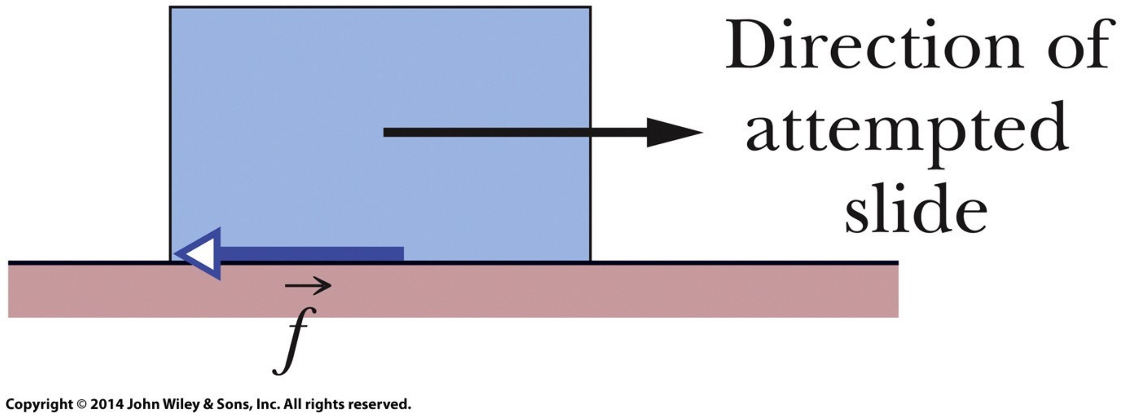

Figure 5-8

5-2 Some Particular Forces

- **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

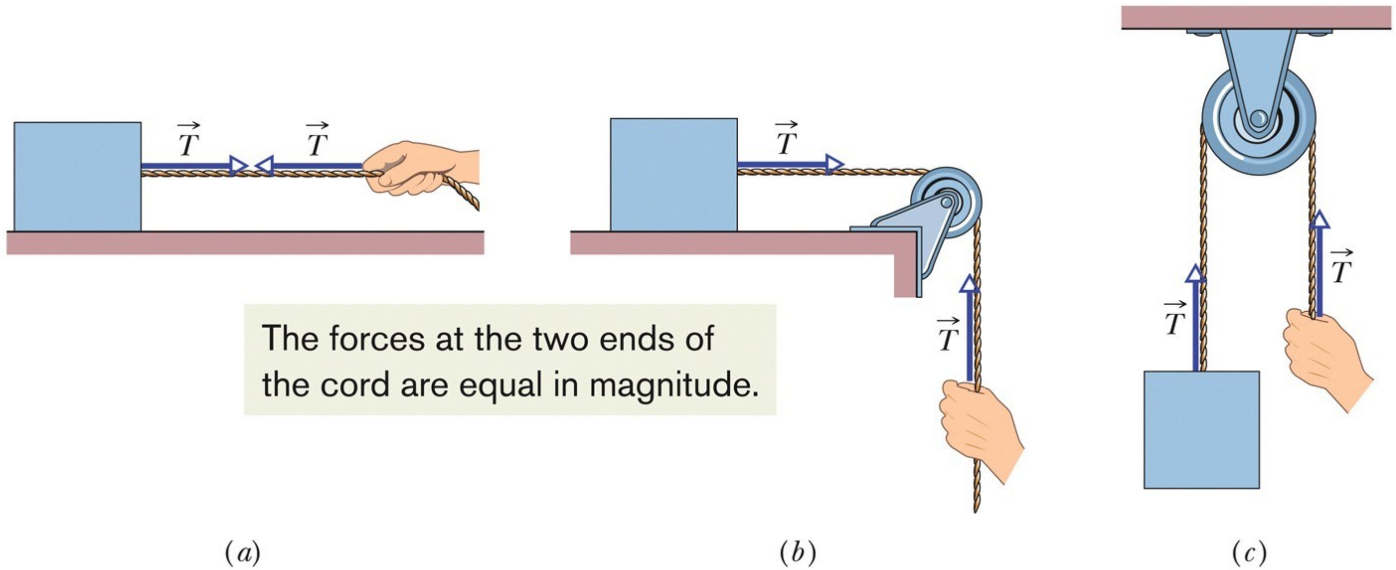

Figure 5-9

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?

Answer: (a) equal to 75 N (b) greater than 75 N (c) less than 75 N

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5-3 Applying Newton's Laws

Learning Objectives

5.14 Identify Newton's third law of motion and third-law of force pairs.

5.15 For an object that moves vertically or on a horizontal or inclined plane, apply Newton's second law to a free-body diagram of the object.

5.16 For an arrangement where a system of several objects moves rigidly together, draw a free-body diagram and apply Newton's second law for the individual objects and also for the system taken as a composite object.

5-3 Applying Newton's Laws

- Objects *interact* when they push or pull on each other:

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

- We can write this law as a scalar or vector relation:

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

Eq. (5-15)

- We call these two forces a **third-law force pair**
- Any time any two objects interact, there is a third-law force pair

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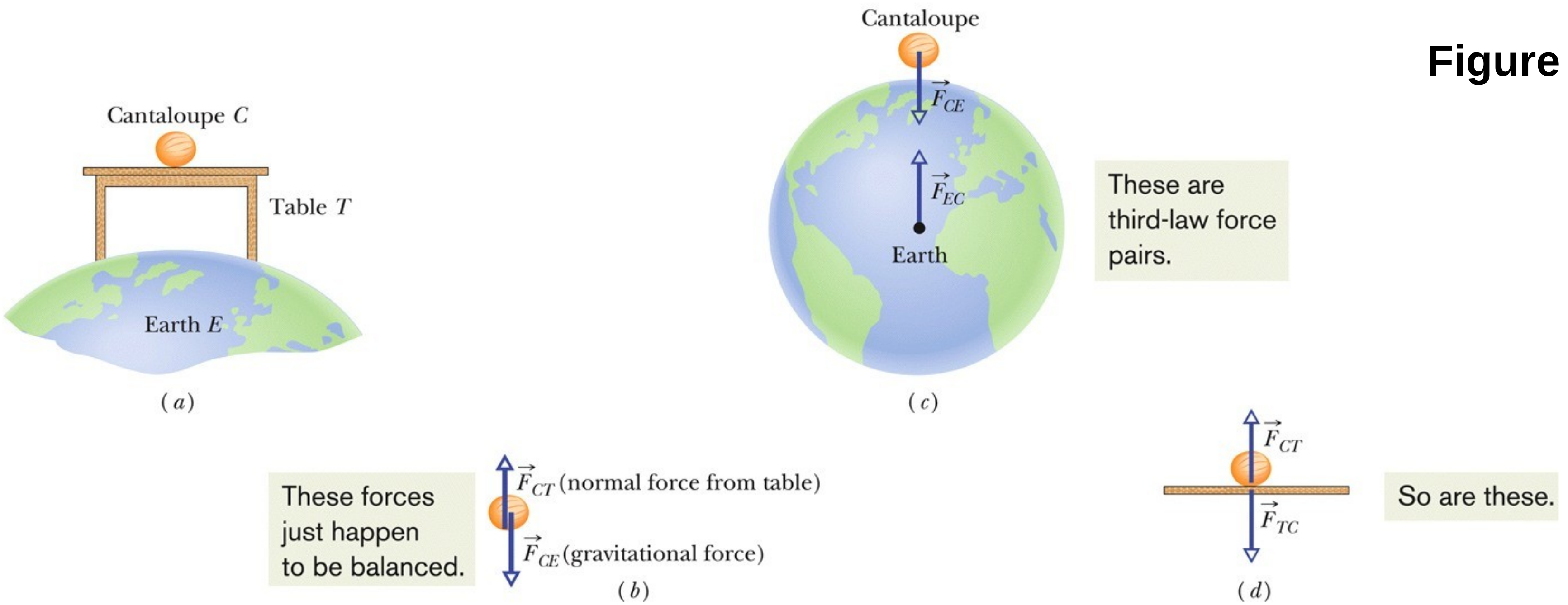
5-3 Applying Newton's Laws

Figure 5-11



- Third-law force pairs:

$$\vec{F}_{CT} = -\vec{F}_{TC} \qquad \text{(cantaloupe–table interaction).}$$

$$\vec{F}_{CE} = -\vec{F}_{EC} \qquad \text{(cantaloupe–Earth interaction).}$$

- This includes the gravitational forces between Earth and the cantaloupe!

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?

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

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5-3 Applying Newton's Laws

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

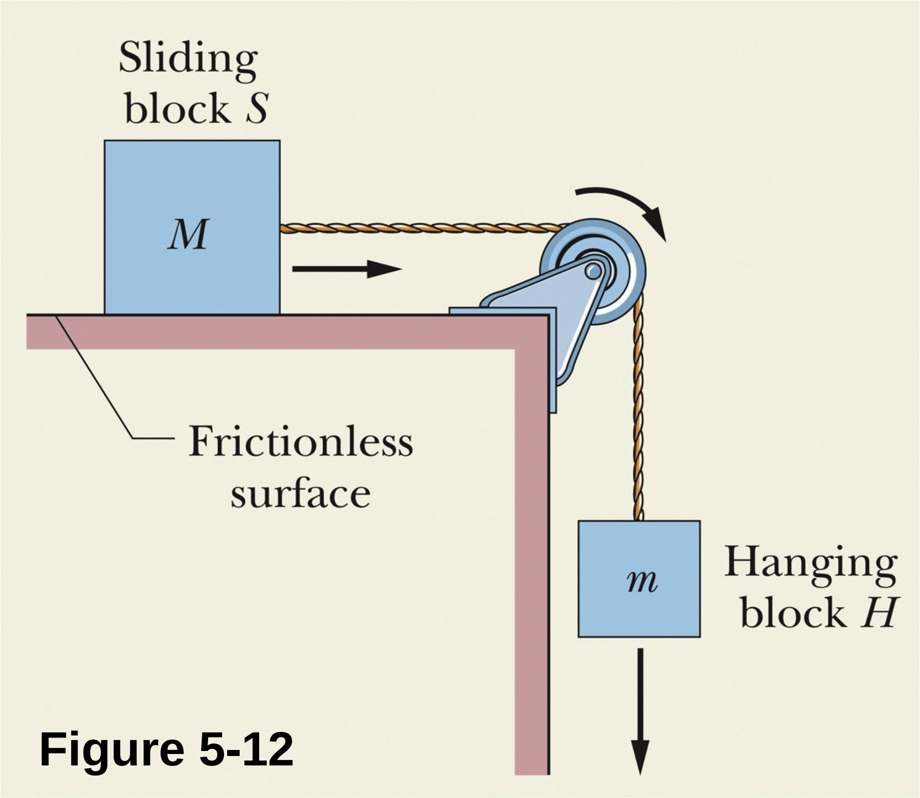


Figure 5-12

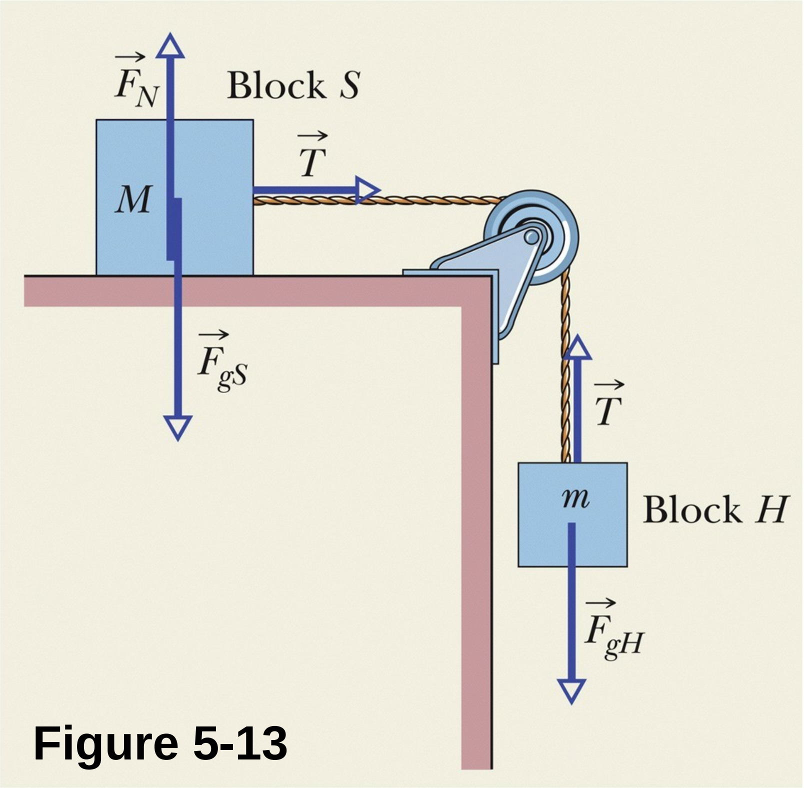


Figure 5-13

5-3 Applying Newton's Laws

- 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 → 2 simultaneous eqs.
- Eliminate unknowns (T) that are the same, and solve for the acceleration

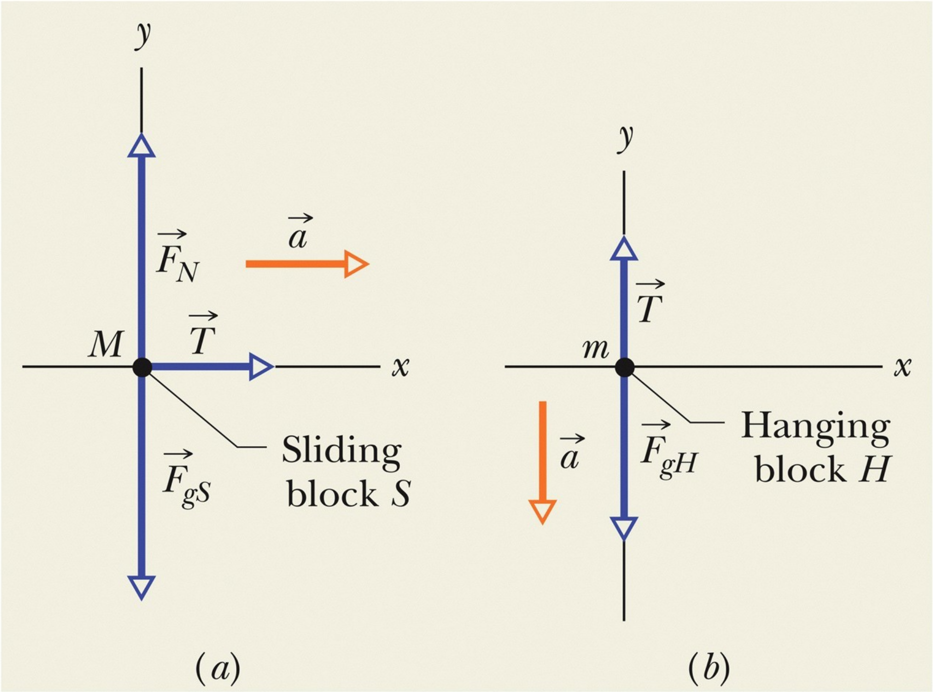


Figure 5-14

5-3 Applying Newton's Laws

- For the sliding block:

$$T = Ma.$$ Eq. (5-18)

- For the hanging block:

$$T - mg = -ma.$$ Eq. (5-20)

- Combining we get:

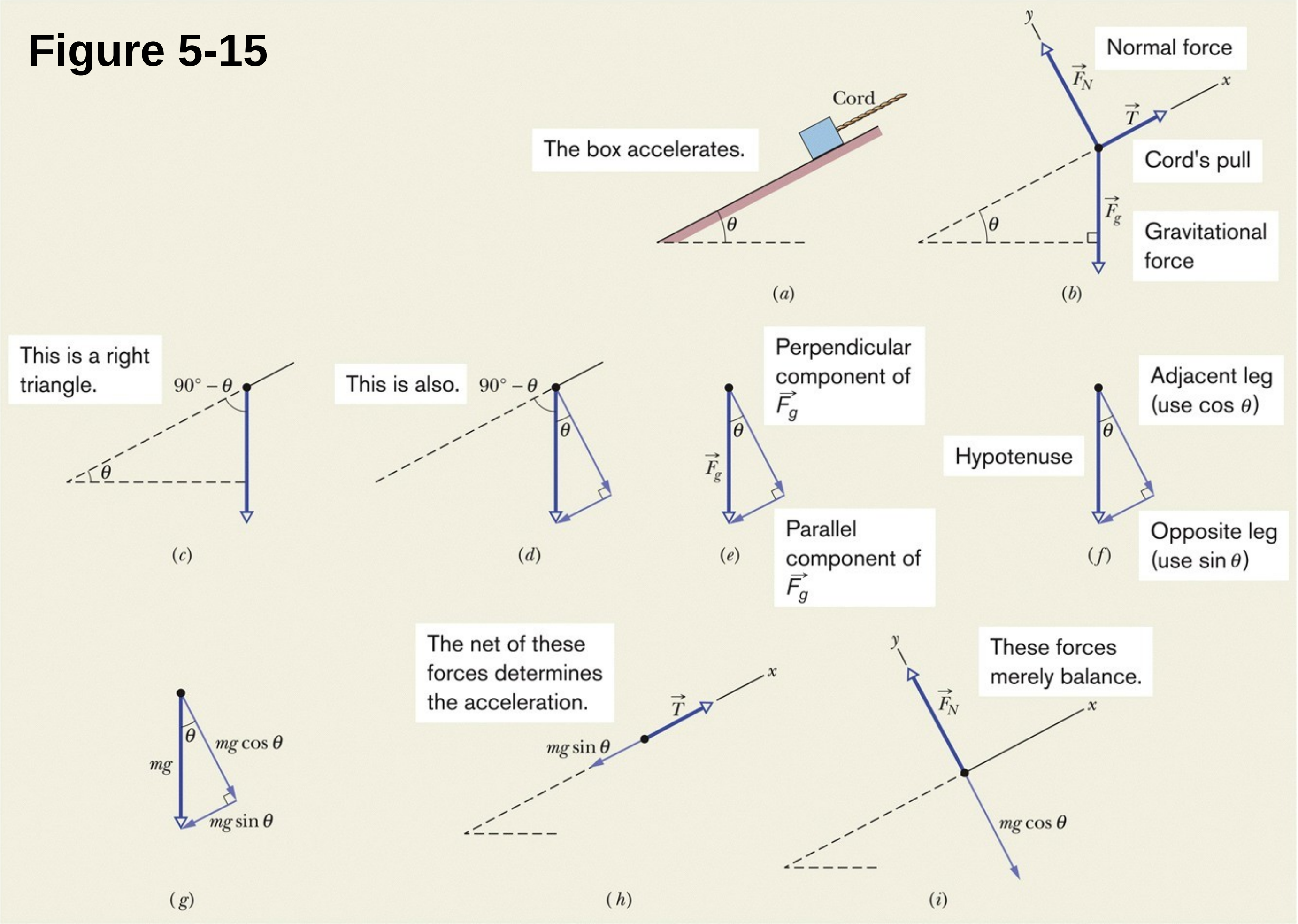
$$a = \frac{m}{M + m} g.$$ Eq. (5-21)

$$T = \frac{Mm}{M + m} g.$$ Eq. (5-22)

- Plugging in we find a = 3.8 m/s^2 and T = 13 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 (e.g., $g = 0$, $M = 0$, $m = \infty$)

5-3 Applying Newton's Laws

Sample Problem A block being pulled up a ramp:



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Sample Problem 5.07 Acceleration of block pushing on block

Some homework problems involve objects that move together, because they are either shoved together or tied together. Here is an example in which you apply Newton's second law to the composite of two blocks and then to the individual blocks.

In Fig. 5-18*a*, a constant horizontal force $\vec{F}_{app}$ of magnitude 20 N is applied to block *A* of mass $m_A = 4.0$ kg, which pushes against block *B* of mass $m_B = 6.0$ kg. The blocks slide over a frictionless surface, along an *x* axis.

(a) What is the acceleration of the blocks?

Serious Error: Because force $\vec{F}_{app}$ is applied directly to block *A*, we use Newton's second law to relate that force to the acceleration $\vec{a}$ of block *A*. Because the motion is along the *x* axis, we use that law for *x* components ($F_{net,x} = ma_x$), writing it as

$$F_{app} = m_A a.$$

However, this is seriously wrong because $\vec{F}_{app}$ is not the only horizontal force acting on block *A*. There is also the force $\vec{F}_{AB}$ from block *B* (Fig. 5-18*b*).

Dead-End Solution: Let us now include force $\vec{F}_{AB}$ by writing, again for the *x* axis,

$$F_{app} - F_{AB} = m_A a.$$

(We use the minus sign to include the direction of $\vec{F}_{AB}$.) Because F_{AB} is a second unknown, we cannot solve this equation for *a*.

Successful Solution: Because of the direction in which force $\vec{F}_{app}$ is applied, the two blocks form a rigidly connected system. We can relate the net force *on the system* to the acceleration *of the system* with Newton's second law. Here, once again for the *x* axis, we can write that law as

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

where now we properly apply $\vec{F}_{app}$ to the system with total mass $m_A + m_B$. Solving for *a* and substituting known values, we find

$$a = \frac{F_{app}}{m_A + m_B} = \frac{20\text{ N}}{4.0\text{ kg} + 6.0\text{ kg}} = 2.0\text{ m/s}^2. \quad \text{(Answer)}$$

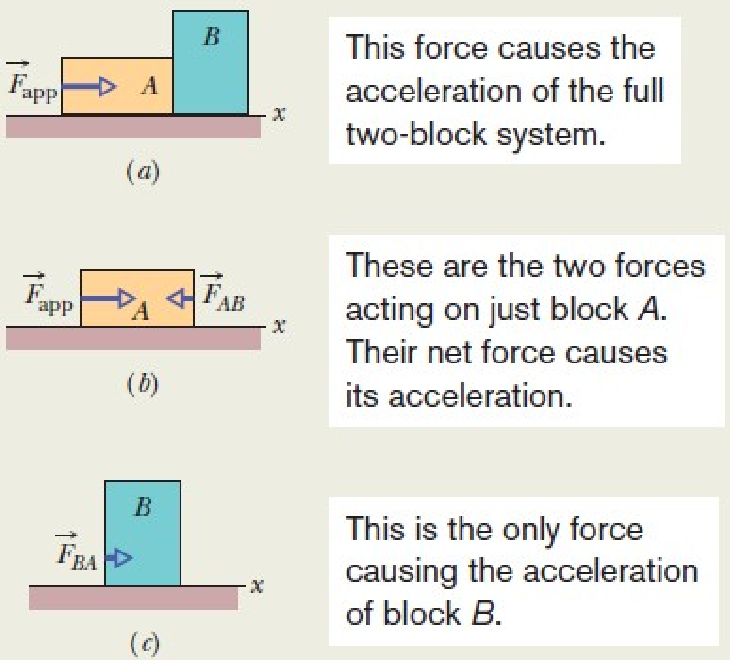

Figure 5-18 (*a*) A constant horizontal force $\vec{F}_{app}$ is applied to block *A*, which pushes against block *B*. (*b*) Two horizontal forces act on block *A*. (*c*) Only one horizontal force acts on block *B*.

Thus, the acceleration of the system and of each block is in the positive direction of the *x* axis and has the magnitude 2.0 m/s^2.

(b) What is the (horizontal) force $\vec{F}_{BA}$ on block *B* from block *A* (Fig. 5-18*c*)?

KEY IDEA

We can relate the net force on block *B* to the block's acceleration with Newton's second law.

Calculation: Here we can write that law, still for components along the *x* axis, as

$$F_{BA} = m_B a,$$

which, with known values, gives

$$F_{BA} = (6.0\ \text{kg})(2.0\ \text{m/s}^2) = 12\ \text{N}. \qquad \text{(Answer)}$$

Thus, force $\vec{F}_{BA}$ is in the positive direction of the *x* axis and has a magnitude of 12 N.

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5 Summary

Newtonian Mechanics

- Forces are pushes or pulls
- Forces cause acceleration

Force

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

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

Mass

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

Newton's Second Law

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

- Free-body diagram represents the forces on one object

Some Particular Forces

- Weight:

$$W = mg$$ **Eq. (5-12)**

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

Newton's Third Law

- Law of force-pairs
- If there is a force **by** *B* **on** *C*, then there is a force **by** *C* **on** *B*:

$$\vec{F}_{BC} = -\vec{F}_{CB}$$ **Eq. (5-15)**