Fundamentals Physics

Eleventh Edition

Halliday

Chapter 5

Force and Motion–I

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5-1 Newton's First and Second Laws

- **Inertial frames**:
  An inertial reference frame is one in which Newton's laws hold.
  The observer (frame of reference) is not accelerating.

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**.

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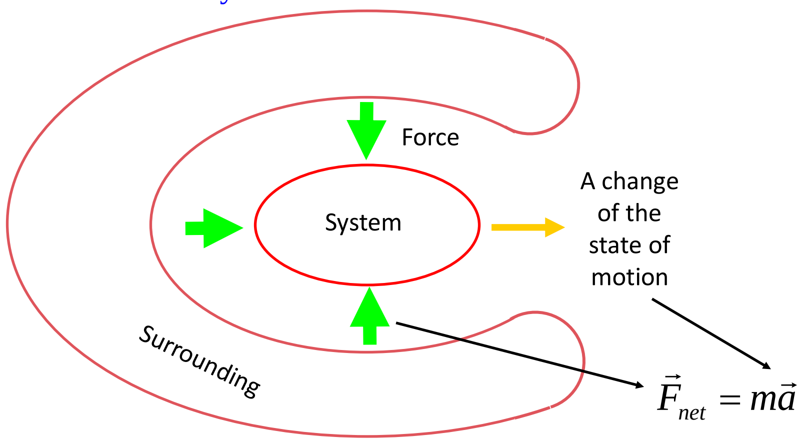
5-1 Newton's First and Second Laws

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



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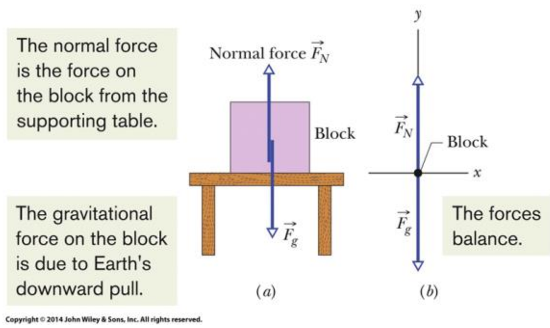
5-2 Some Particular Forces

- The **gravitational force**, written as a vector:

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

- 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



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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

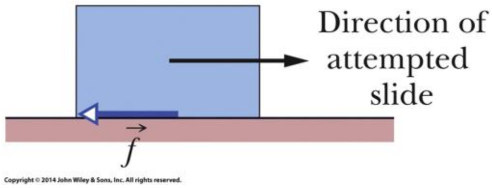

Figure 5-8

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

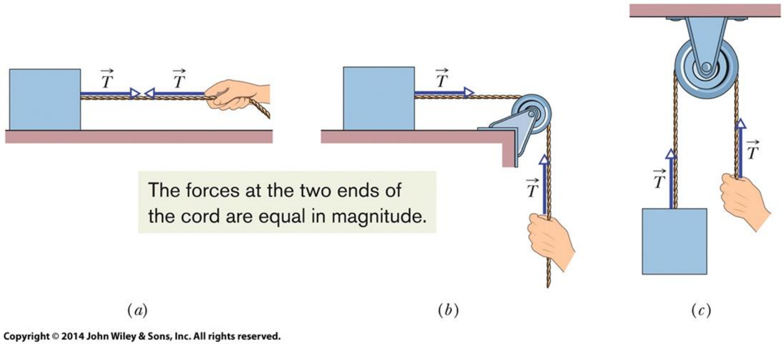

Figure 5-9

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5-3 Applying Newton's Laws (1 of 20)

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.

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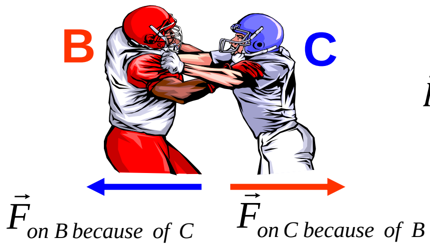
5-3 Applying Newton's Laws (2 of 20)

- 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:



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

Equation (5-15)

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

5-3 Applying Newton's Laws (3 of 20)

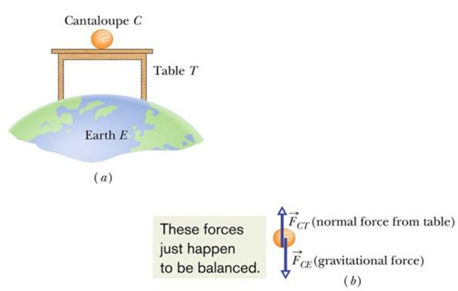


Figure 5-11

- Third-law force pairs:

$$\vec{F}_{CT} = -\vec{F}_{TC} : \text{cantaloupe} - \text{table}$$
$$\vec{F}_{CE} = -\vec{F}_{EC} : \text{cantaloupe} - \text{Earth}$$

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

Interlude: Gravitational Acceleration

$$F_G = G\frac{m_1 m_2}{r^2}$$

$$F_G = G\frac{M_E m}{r^2}$$

$$F_G = G\frac{M_E m}{(R_E + h)^2} \approx \left[G\frac{M_E}{(R_E)^2}\right] m = gm = (9.8)m$$

$G = 6.67408 \times 10^{-11}$

$M_E = 5.972 \times 10^{24}\ kg$

$R_E = 6380\ km$

Interlude: Gravitational Acceleration

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$G = 6.67408 \times 10^{-11}$

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5-3 Applying Newton's Laws (4 of 20)

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

5-3 Applying Newton's Laws (5 of 20)

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

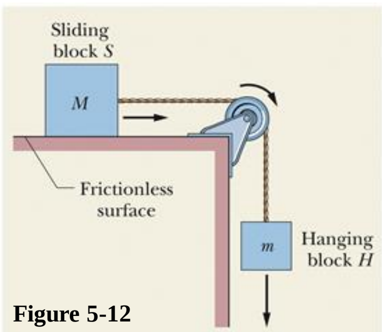


Figure 5-12

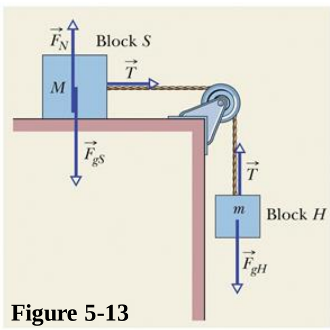


Figure 5-13

5-3 Applying Newton's Laws (6 of 20)

- 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 equations.
- Eliminate unknowns (T) that are the same, and solve for the acceleration

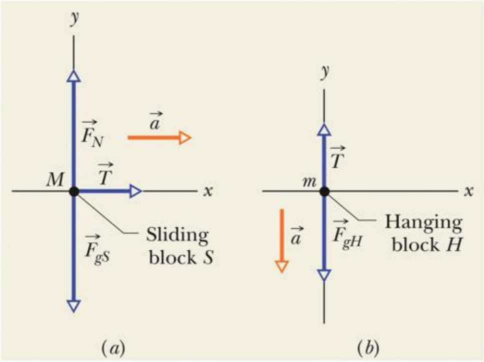


Figure 5-14

5-3 Applying Newton's Laws (7 of 20)

- For the sliding block:

$$T = Ma.$$ **Equation (5-18)**

- For the hanging block:

$$mg - T = ma.$$ **Equation (5-20)**

- Combining we get:

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

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

5-3 Applying Newton's Laws (8 of 20)

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

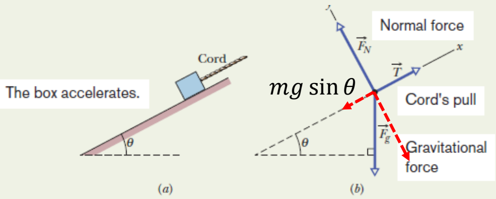
- Plugging in we find $a = 3.8 \text{ m/s}^2$ and $T = 13 \text{ N}$
- Does this make sense? Check that dimensions are correct, check that $a < g$, check that $T < mg$ (otherwise acceleration would be upward), check limiting cases $(\text{e.g., } g = 0,\ M = 0,\ m = \infty)$

5-3 Applying Newton's Laws (9 of 20)

Sample Problem A block being pulled up a ramp:

Cord accelerates block up a ramp

In Fig. 5-15*a*, a cord pulls on a box of sea biscuits up along a frictionless plane inclined at $\theta = 30°$. The box has mass $m = 5.00$ kg, and the force from the cord has magnitude $T = 25.0$ N. What is the box's acceleration component a along the inclined plane?



5-3 Applying Newton's Laws (10 of 20)

Sample Problem A block being pulled up a ramp:

From Fig. 5-15*h*, we write Newton's second law ($\vec{F}_{net} = m\vec{a}$) for motion along the *x* axis as

$$T - mg\sin\theta = ma. \quad (5\text{-}24)$$

Substituting data and solving for *a*, we find

$$a = 0.100\ \text{m/s}^2, \quad \text{(Answer)}$$

where the positive result indicates that the box accelerates up the plane.

5-3 Applying Newton's Laws (11 of 20)

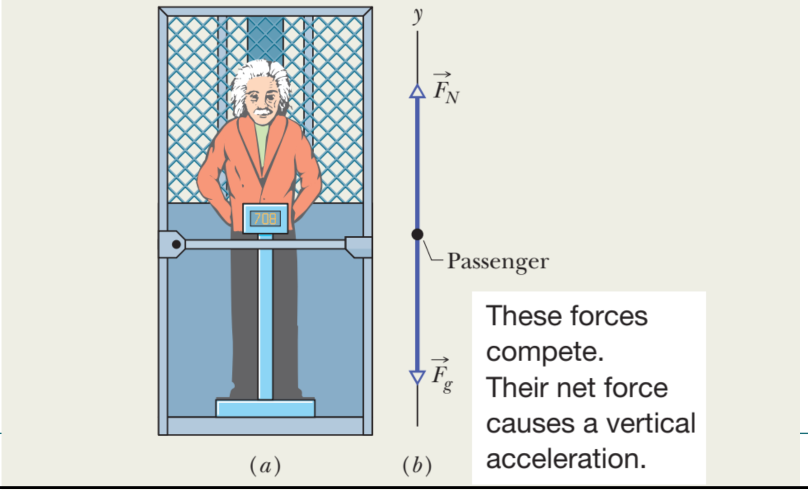
Sample Problem Forces within an elevator cab

In Fig. 5-17*a*, 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.

5-3 Applying Newton's Laws (12 of 20)

Sample Problem Forces within an elevator cab



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5-3 Applying Newton's Laws (13 of 20)

Sample Problem Forces within an elevator cab

The reading is equal to the magnitude of the normal force $\vec{F}_N$ on the passenger from the scale. The only other force acting on the passenger is the gravitational force $\vec{F}_g$, as shown in the free-body diagram of Fig. 5-17*b*.

$$F_N - F_g = ma$$

or

$$F_N = F_g + ma.$$

or

$$F_N = m(g + a) \qquad (5\text{-}28)$$

for any choice of acceleration *a*. If the acceleration is upward, *a* is positive; if it is downward, *a* is negative.

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5-3 Applying Newton's Laws (14 of 20)

Sample Problem Forces within an elevator cab

(b) What does the scale read if the cab is stationary or moving upward at a constant 0.50 m/s?

$$F_N = (72.2\text{ kg})(9.8\text{ m/s}^2 + 0) = 708\text{ N}.$$

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

$$F_N = (72.2\text{ kg})(9.8\text{ m/s}^2 + 3.20\text{ m/s}^2) = 939\text{ N},$$

and for $a = -3.20\text{ m/s}^2$, it gives

$$F_N = (72.2\text{ kg})(9.8\text{ m/s}^2 - 3.20\text{ m/s}^2) = 477\text{ N}.$$

5-3 Applying Newton's Laws (15 of 20)

Sample Problem Forces within an elevator cab

(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 $a_{p,cab}$ of his acceleration as measured in the frame of the cab? Does $\vec{F}_{net} = m\vec{a}_{p,cab}$?

Calculation: The magnitude F_g of the gravitational force on the passenger does not depend on the motion of the passenger or the cab; so, from part (b), F_g is 708 N. From part (c), the magnitude F_N of the normal force on the passenger during the upward acceleration is the 939 N reading on the scale. Thus, the net force on the passenger is

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

5-3 Applying Newton's Laws (16 of 20)

Sample Problem Forces within an elevator cab

(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 $a_{p,cab}$ of his acceleration as measured in the frame of the cab? Does $\vec{F}_{net} = m\vec{a}_{p,cab}$?

$a_{p,cab}$ relative to the frame of the cab is zero. Thus, in the noninertial frame of the accelerating cab, F_{net} is not equal to $ma_{p,cab}$, and Newton's second law does not hold.

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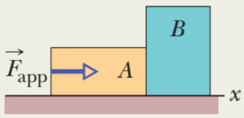
5-3 Applying Newton's Laws (17 of 20)

Sample Problem Acceleration of block pushing on block

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*)

This force causes the acceleration of the full two-block system.

(a) What is the acceleration of the blocks?

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5-3 Applying Newton's Laws (18 of 20)

Sample Problem Acceleration of block pushing on block

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

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

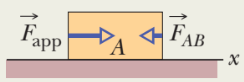
where now we properly apply $\vec{F}_{app}$ to the system with total mass $m_A + m_B$. Solving for a and substituting known values, we find

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

5-3 Applying Newton's Laws (19 of 20)

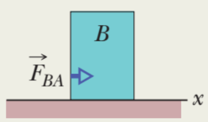
Sample Problem Acceleration of block pushing on block

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



(b)

These are the two forces acting on just block *A*. Their net force causes its acceleration.

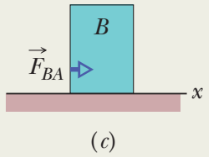


(c)

This is the only force causing the acceleration of block *B*.

5-3 Applying Newton's Laws (20 of 20)

Sample Problem Acceleration of block pushing on block



This is the only force causing the acceleration of block *B*.

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

which, with known values, gives

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

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

5 Summary (1 of 5)

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 5)

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 5)

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

5 Summary (4 of 5)

Some Particular Forces

- Weight:

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

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

5 Summary (5 of 5)

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*:

$$\vec{F}_{BC} = -\vec{F}_{CB}$$ **Equation (5-12)**

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