Ch.5: The Laws of Motion

Physics 103: Classical Mechanics

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Outline

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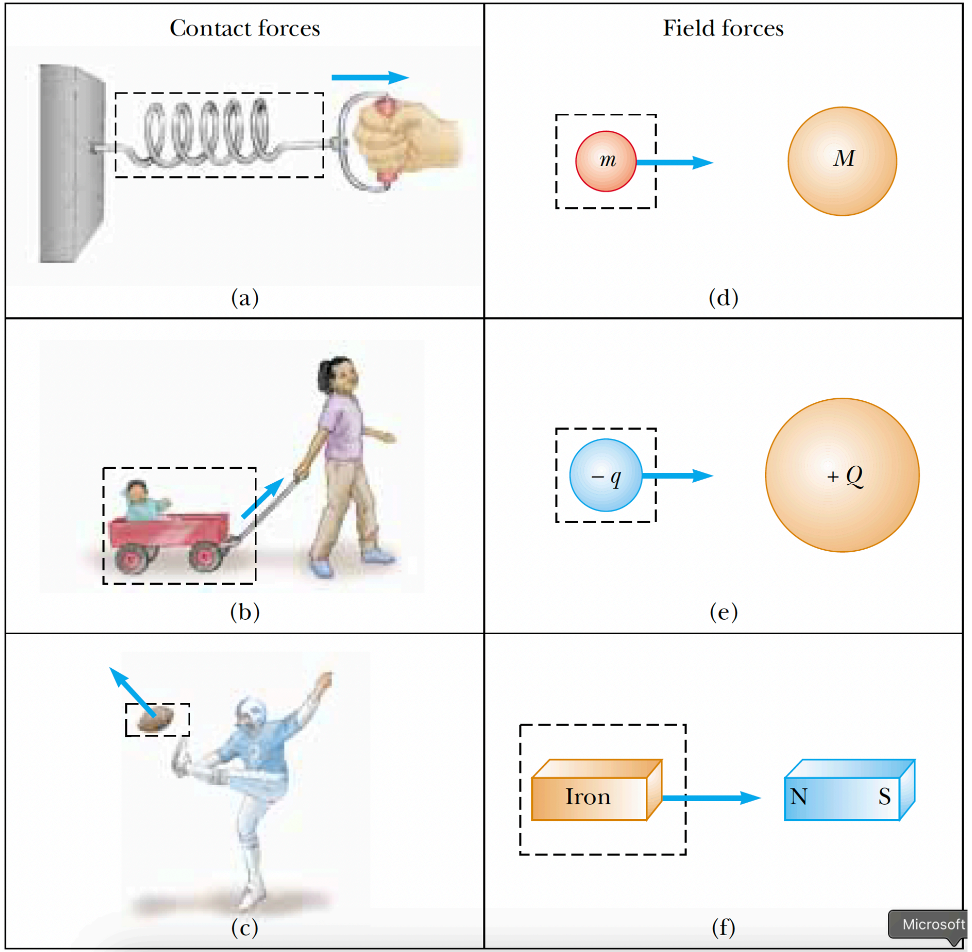
1.1 What is a Force?

- A force is a push or a pull.
- A force can cause an object to:
  - accelerate
  - decelerate
  - change direction
  - deform
- Force is a vector quantity represented by the symbol F.
- It is measured in the SI unit of newton (N). One newton is defined as the force that, when acting on a mass of 1 kg, produces an acceleration of 1 m/s^2.

1.2 Contact and Field Forces



1.3 Net Force

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What happens when several forces act simultaneously on an object?

- In this case, the object accelerates only if the **net force** acting on it is *not* equal to zero.
- The net force acting on an object is defined as the vector sum of all forces acting on the object.

$$\Sigma\vec{\boldsymbol{F}} = \vec{\boldsymbol{F}}_1 + \vec{\boldsymbol{F}}_2 + \vec{\boldsymbol{F}}_3 + \quad \ldots$$

- We sometimes refer to the net force as the total force or the resultant force.

1.4 Equilibrium

What happens when the net force acting on an object is zero?

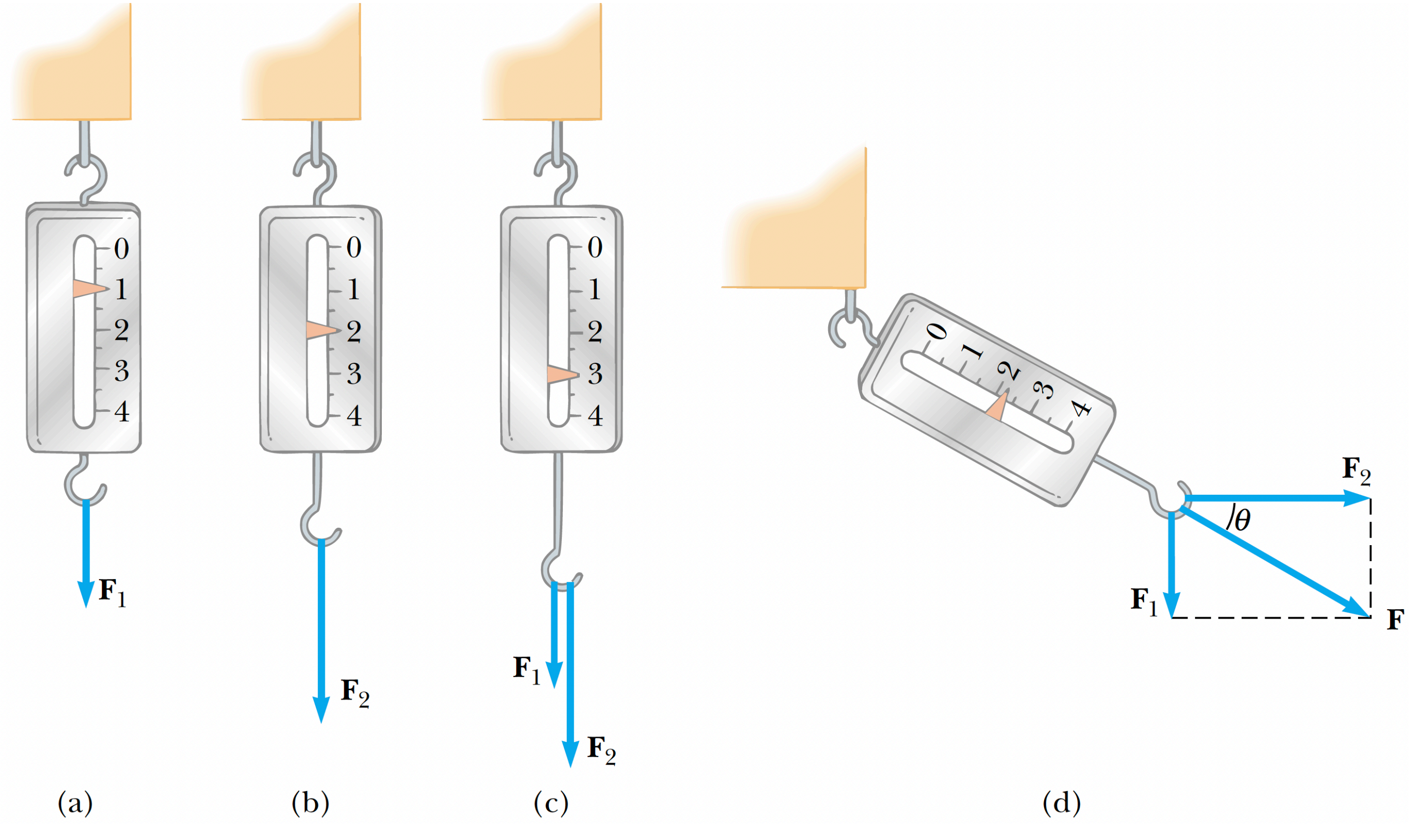
- If the net force is zero, the acceleration of the object is zero and its velocity remains constant:

$$\Sigma\vec{\boldsymbol{F}} = 0 \quad \Rightarrow \quad \vec{\boldsymbol{a}} = 0 \quad \Rightarrow \quad \vec{\boldsymbol{v}} = \text{constant}$$

- If the object at rest, it remains at rest.
- If the object is in motion, it remains to move with constant velocity.
- When the velocity of an object is constant, the object is said to be in **equilibrium**.

1.5 Measuring the Strength of a Force

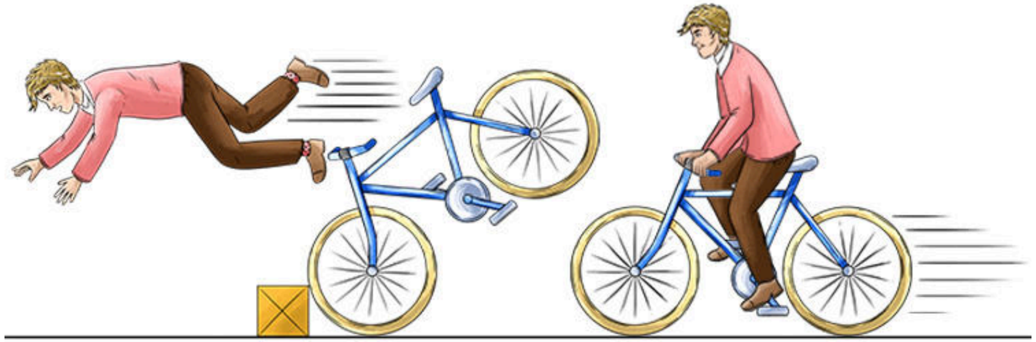
The strength of a force can be measured with a device such as a spring scale.



2.1 Statement of the Law

An object at rest will remain at rest, and an object in motion will remain in motion with a constant velocity unless acted upon by a net external force.

- The tendency of an object to resist any attempt to change its velocity is called **inertia**.



2.2 What is Mass?

- Mass is a quantitative measure of inertia, and it specifies how much resistance an object exhibits to changes in its velocity.
- The greater the mass of an object, the less that object accelerates under the action of a given applied force.
- For example, at constant force

$$\begin{aligned} \text{If} \quad & m = 3 \text{ kg} \quad \text{and} \quad a = 4 \ \ \text{m/s}^2 \\ \text{then at} \quad & m = 6 \text{ kg} \\ \text{We get} \quad & a = 2 \ \ \text{m/s}^2 \end{aligned}$$

1. The Concept of Force

2. Newton's First Law

3. Newton's Second Law

4. Newton's Third Law

5. Some Applications of Newton's Laws

6. Forces of Friction

7. Suggested Problems

3.1 Statement of the Law

The acceleration of an object is directly proportional to the force acting on it.

$$\boldsymbol{\Sigma \vec{F}} \propto \boldsymbol{\vec{a}}$$

The proportionality constant is the mass (inertia) of the object. Therefoere,

$$\Sigma \boldsymbol{\vec{F}} = m\boldsymbol{\vec{a}}$$

Expanding into components gives,

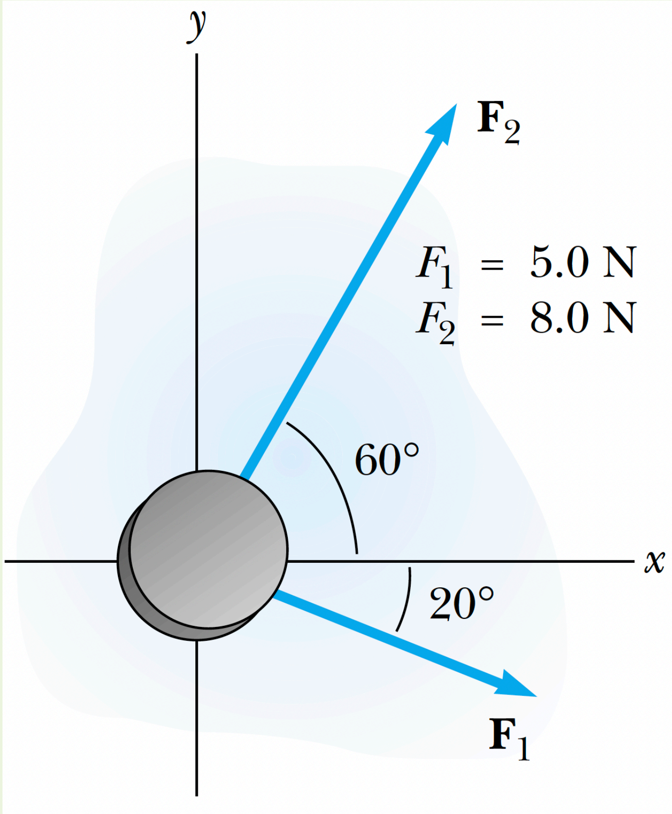
$$\Sigma F_x = ma_x, \quad \Sigma F_y = ma_y, \quad \Sigma F_z = ma_z$$

3.2 Example

Example 3.1

A hockey puck having a mass of 0.3 kg slides on the horizontal, frictionless surface of an ice rink. Two hockey sticks strike the puck simultaneously, exerting the forces on the puck shown in the Figure. The force F1 has a magnitude of 5 N, and the force F2 has a magnitude of 8 N.

Determine both the magnitude and the direction of the puck's acceleration.



3.2 Example

Solution 3.1

- **Setp 1**: Find the net force along the x-axis and y-axis.

$$\Sigma F_x = F_{1x} + F_{2x} = 5\cos(-20°) + 8\cos(60°) = 8.7N$$

$$\Sigma F_y = F_{1y} + F_{2y} = 5\sin(-20°) + 8\sin(60°) = 5.2N$$

- **Step 2**: Find the acceleration components using Newton's second law.

$$a_x = \frac{\Sigma F_x}{m} = \frac{8.7N}{0.3\ \text{kg}} = 29\ \text{m/s}^2$$

$$a_y = \frac{\Sigma F_y}{m} = \frac{5.2N}{0.3\ \text{kg}} = 17\ \text{m/s}^2$$

3.2 Example

- **Step 3**: Find the magnitude and direction of the acceleration.

$$a = \sqrt{a_x^2 + a_y^2} = \sqrt{(29)^2 + (17)^2} = 34 \text{ m/s}^2$$

$$\theta = \tan^{-1}\left(\frac{a_y}{a_x}\right) = \tan^{-1}\left(\frac{17}{29}\right) = 30^\circ$$

3.3 The Gravitational Force and Weight

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- The gravitational force (weight) acting on an object of mass m near the surface of the Earth is given by:

$$\Sigma \vec{F} = m\vec{a}$$

Since the only force is gravitational, and the acceleration is due to gravity of the Earth, we have

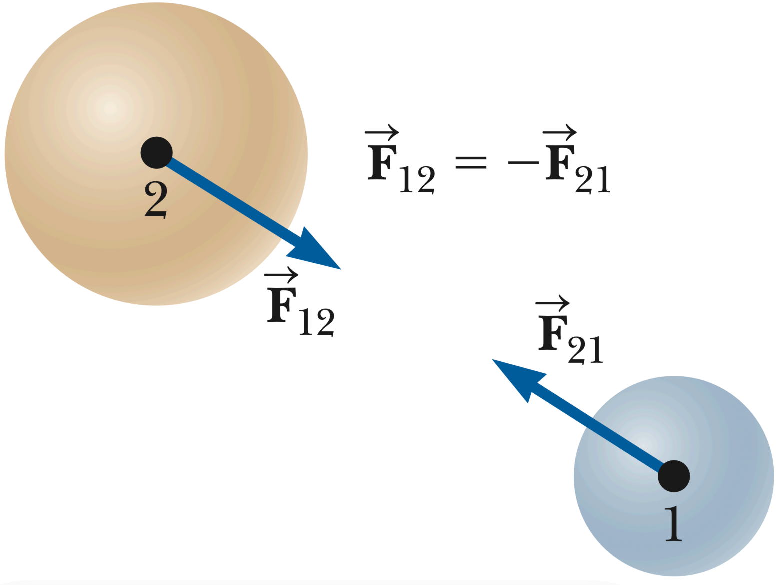
$$\overrightarrow{W} \equiv \vec{F}_g = m\vec{g}$$

- For example, the weight of a 70-kg person on the surface of the Earth is:

$$W = (70 \text{ kg})(9.8 \text{ m/s}^2) = 686N$$

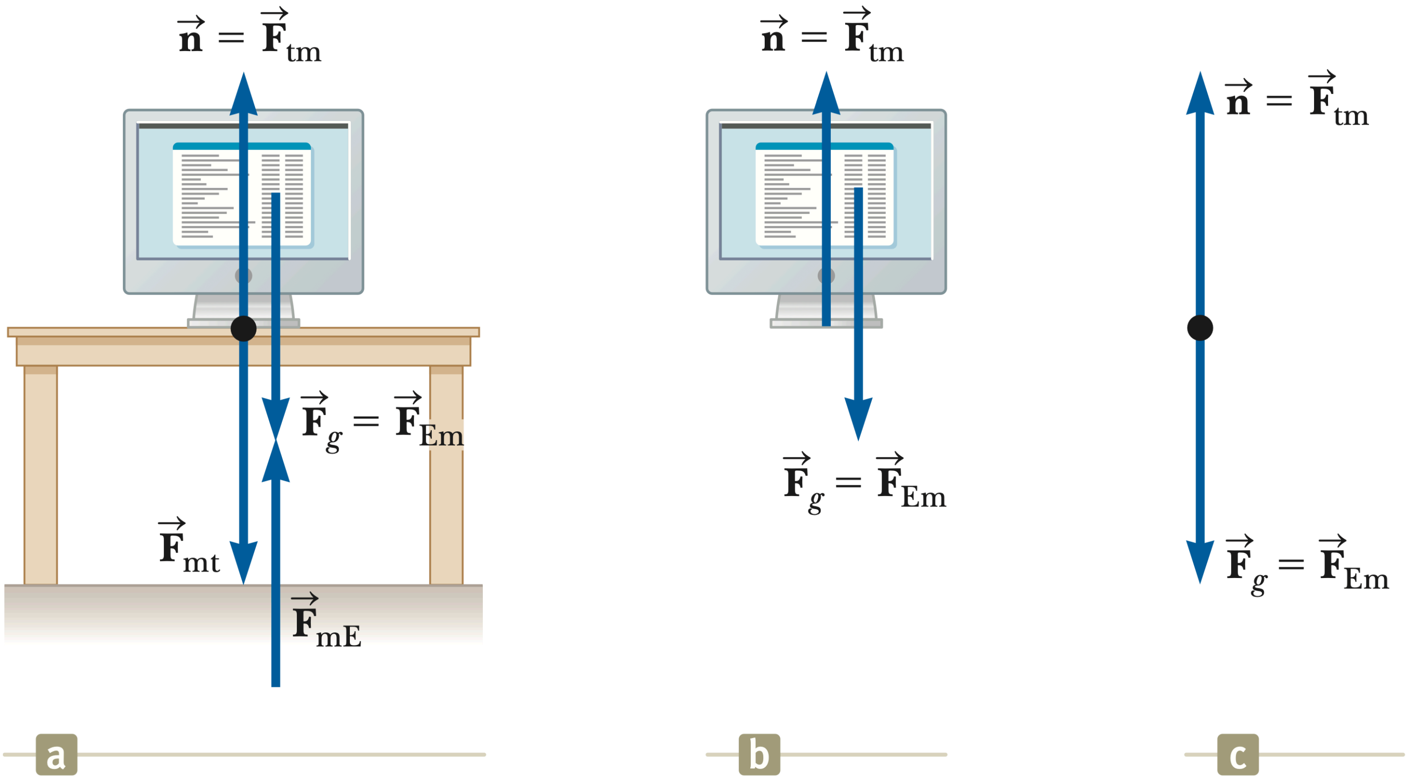
4.1 Statement of the Law

If two objects interact, the force $\vec{F}_{12}$ exerted by object 1 on object 2 is equal in magnitude and opposite in direction to the force $\vec{F}_{21}$ exerted by object 2 on object 1.



$$\vec{\mathbf{F}}_{12} = -\vec{\mathbf{F}}_{21}$$

4.1 Statement of the Law



t: table **m**: monitor **E**: Earth **g**: gravity

4.1 Statement of the Law

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Example 4.2

A large man and a small boy stand facing each other on frictionless ice. They put their hands together and push against each other so that they move apart.

Who moves away faster?

Solution 4.2

- The forces they exert on each other are equal in magnitude and opposite in direction.
- Since $a = F/m$, the smaller mass (the boy) will have the greater acceleration and will move away faster.

5.1 Objects in Equilibrium

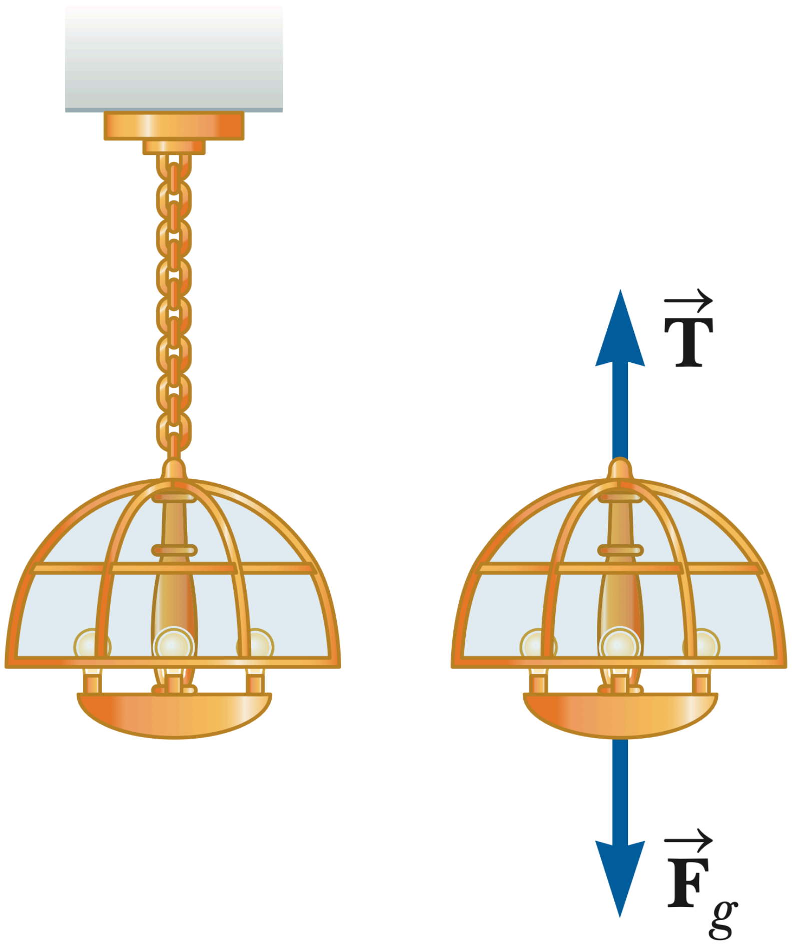
- An object is in equilibrium when the net force acting on it is zero.

$$\sum \vec{\boldsymbol{F}} = 0$$

- In the case of a lamp suspended from a ceiling by a chain of negligible mass, the force of gravity on the lamp is balanced by the tension in the chain.

$$\sum F_y = T - F_g = 0$$

$$\Rightarrow \quad T = F_g$$



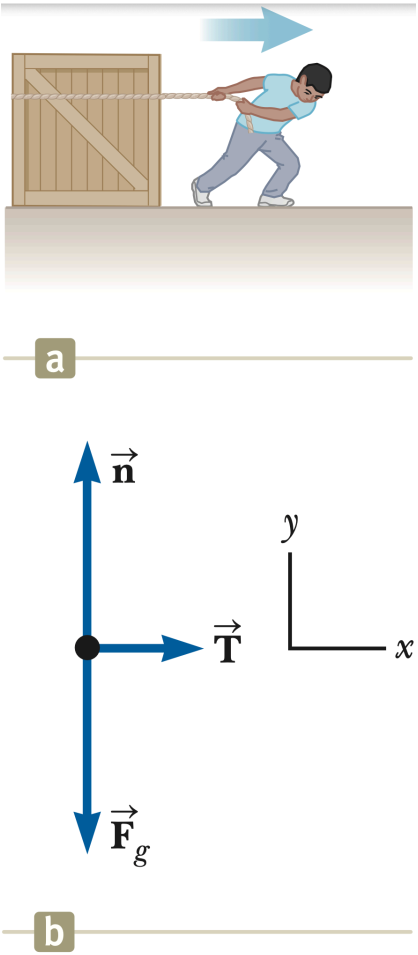
5.2 Objects Experiencing a Net Force

- An object is accelerating when the net force acting on it is not zero.

$$\sum \vec{F} = m\vec{a}$$

- In the case of a box being pulled across a horizontal surface to the right, we have:

$$\sum F_x = T = ma_x \quad \Rightarrow \quad a_x = T/m$$
$$\sum F_y = n - F_g = 0 \quad \Rightarrow \quad n = F_g$$

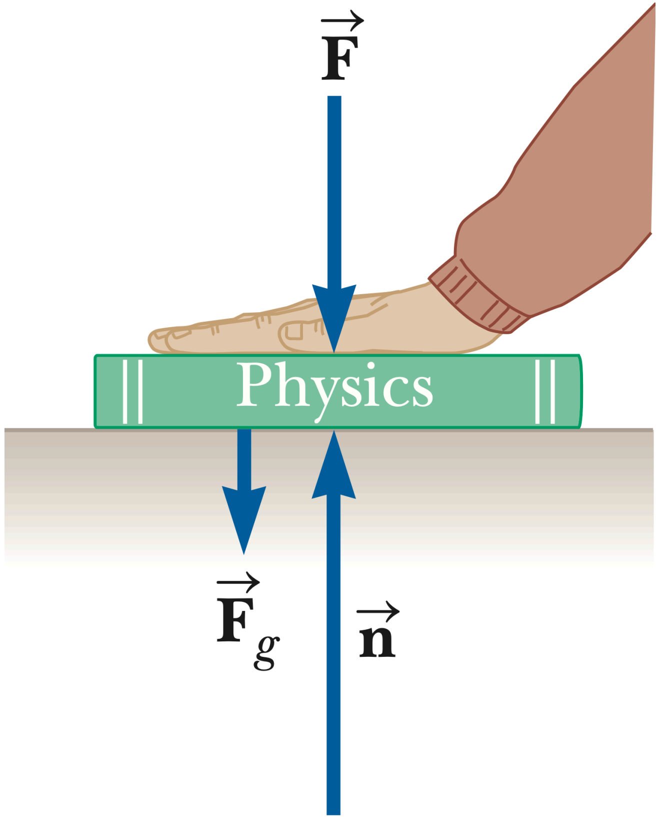


5.2 Objects Experiencing a Net Force

- When a force pushes vertically downward on another object, the normal force on the object is greater than the object's weight,

$$\sum F_y = n - F_g - F = 0$$

$$\Rightarrow \quad n = F_g + F$$



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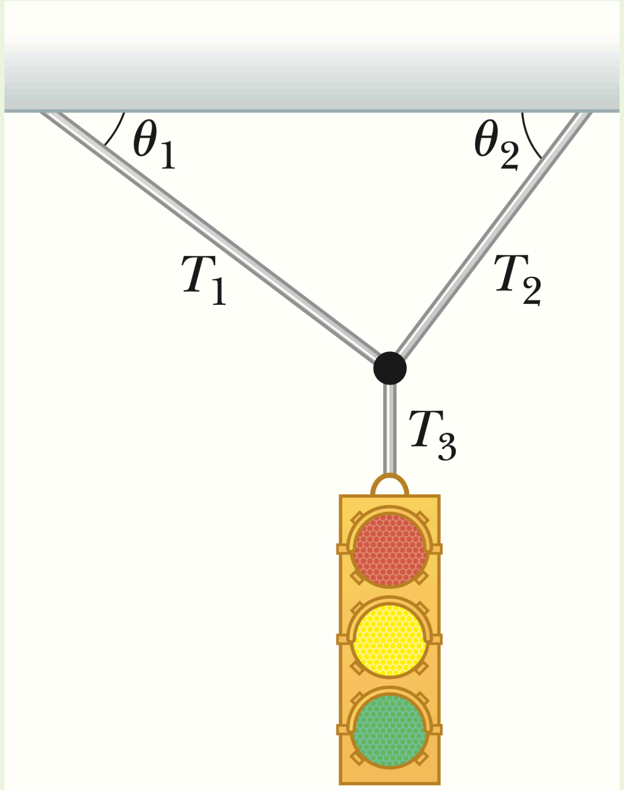
Example 5.3

A traffic light weighing 122 N hangs from a cable tied to two other cables fastened to a support, as in the Figure. The upper cables make angles of 37° and 53° with the horizontal. These upper cables are not as strong as the vertical cable, and will break if the tension in them exceeds 100 N. Will the traffic light remain hanging in this situation, or will one of the cables break?



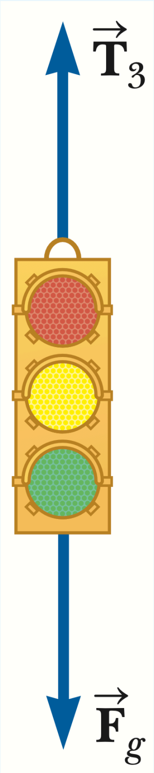
5.3 Examples

Solution 5.3

- For simplicity, we first consider only the vertical cable.

$$\sum F_y = T_3 - F_g = 0$$

$$\Rightarrow \quad T_3 = F_g = 122N$$



5.3 Examples

Solution 5.3

- Next, we consider the two angled cables,

  (1) $\sum F_x = T_2 \cos\theta_2 - T_1 \cos\theta_1 = 0$

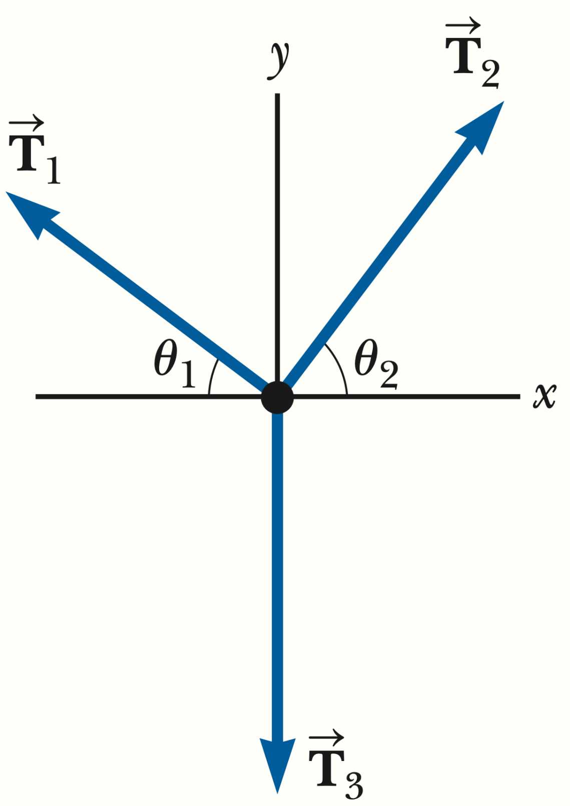
  (2) $\sum F_y = T_2 \sin\theta_2 + T_1 \sin\theta_1 - F_g = 0$

- We have two equations and two unknowns, T_1 and T_2. From equation (1), we have

(3) $$T_2 = T_1 \frac{\cos\theta_1}{\cos\theta_2}$$

- Substituting this into equation (2) gives

$$\left(T_1 \frac{\cos\theta_1}{\cos\theta_2}\right) \sin\theta_2 + T_1 \sin\theta_1 = F_g$$



5.3 Examples

$$T_1(\cos\theta_1 \tan\theta_2 + \sin\theta_1) = F_g$$

- Solving for T_1 gives

$$T_1 = \frac{F_g}{\cos\theta_1 \tan\theta_2 + \sin\theta_1} = \frac{122}{\cos 37° + \tan 53° + \sin 37°} = 73.4 \text{ N}$$

- To find T_2, we substitute the value of T_1 into Eq(3):

$$T_2 = T_1 \frac{\cos\theta_1}{\cos\theta_2} = 73.4 \frac{\cos 37°}{\cos 53°} = 97.4 \text{ N}$$

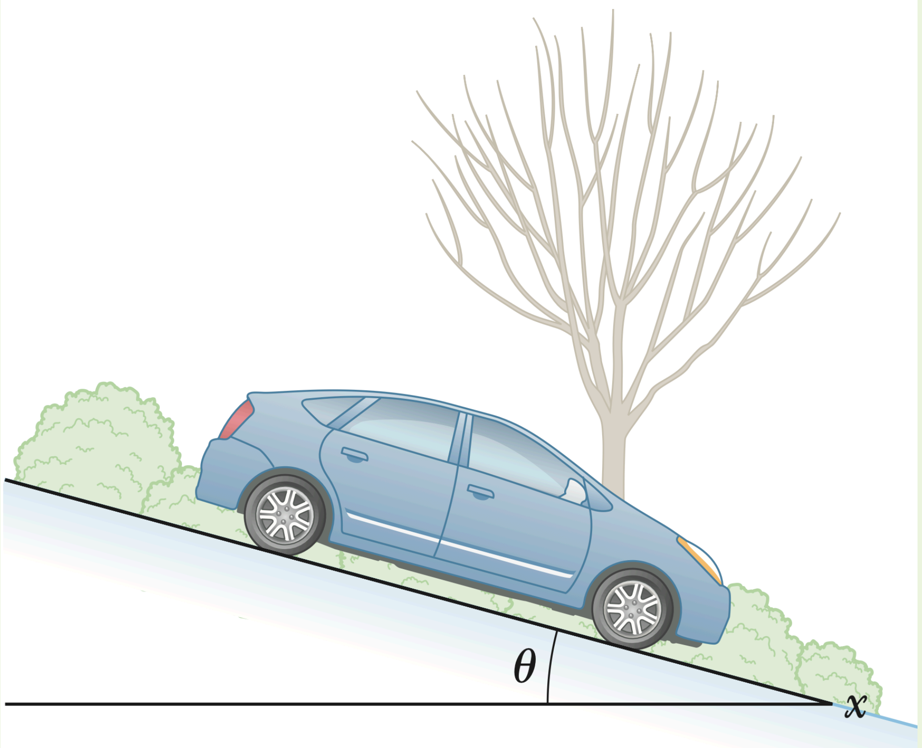
- Since neither tension exceeds 100 N, the traffic light will remain hanging in this situation.

5.3 Examples

Example 5.4

A car of mass (m) is on an icy driveway inclined at an angle (θ), as in the Figure.

(A) Find the acceleration of the car, assuming that the driveway is frictionless.



5.3 Examples

Solution 5.4

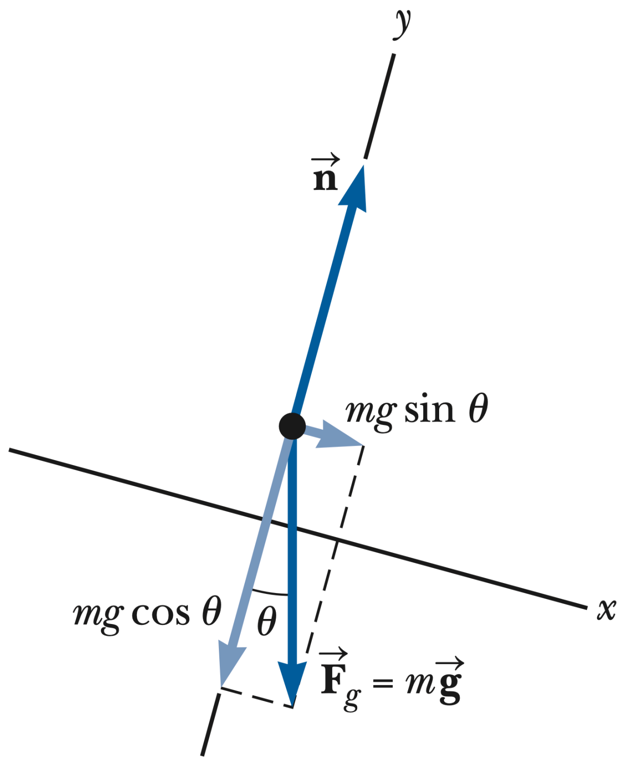
- Analyzing the forces in the x and y axes,

$$\sum F_x = mg\sin\theta - 0 = ma_x \quad (1)$$

$$\sum F_y = n - mg\cos\theta = 0 \quad (2)$$

From Eq (1), we solve for a_x:

$$a_x = g\sin\theta \quad (3)$$



5.3 Examples

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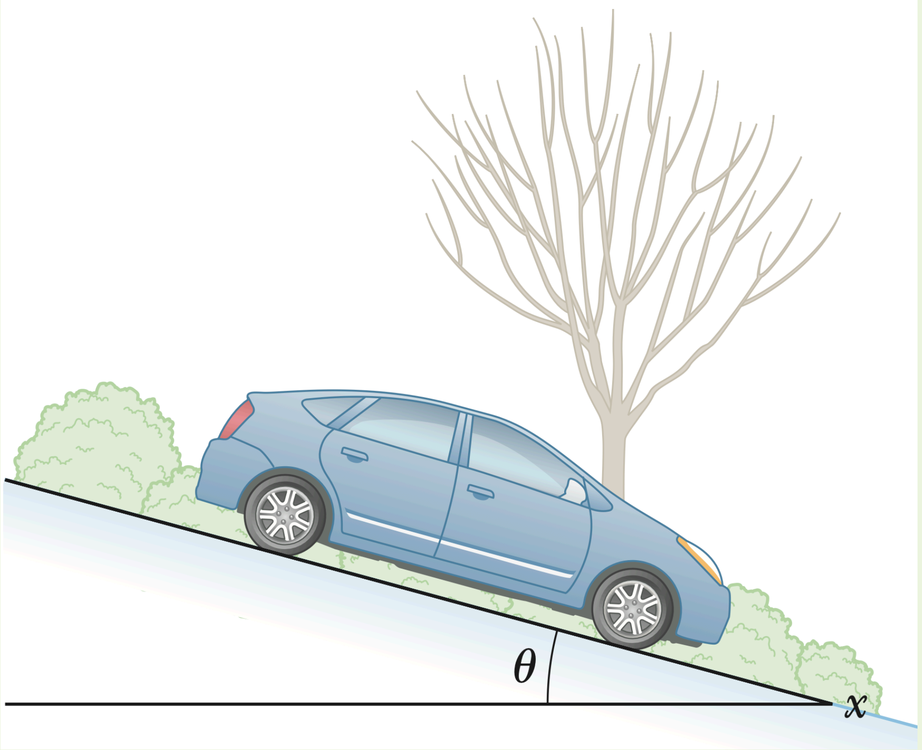
Example 5.5

Suppose the car is released from rest at the top of the incline, and the distance from the car's front bumper (مقدمة السيارة) to the bottom of the incline is d.

(B) How long does it take the front bumper to reach the bottom, and

(C) What is the car's speed as it arrives there?



5.3 Examples

- The distance d can be found from the equation of motion:

$$x_f = x_i + v_i t + \frac{1}{2} a_x t^2$$

$$\Rightarrow d = (x_f - x_i) = \frac{1}{2} a_x t^2$$

- From part (A), we have $a_x = g \sin\theta$. Therefore,

$$d = \frac{1}{2}(g \sin\theta) t^2$$

$$\Rightarrow t = \sqrt{\frac{2d}{g \sin\theta}}$$

5.3 Examples

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- (C) The speed of the car at the bottom of the incline can be found from the equation of motion:

$$v_f = v_i + a_x t$$

$$\Rightarrow v_f = 0 + (g\sin\theta)t$$

- Substituting the value of t from part (B) gives:

$$v_f = (g\sin\theta)\sqrt{\frac{2d}{g\sin\theta}} = \sqrt{2dg\sin\theta}$$

5.3 Examples

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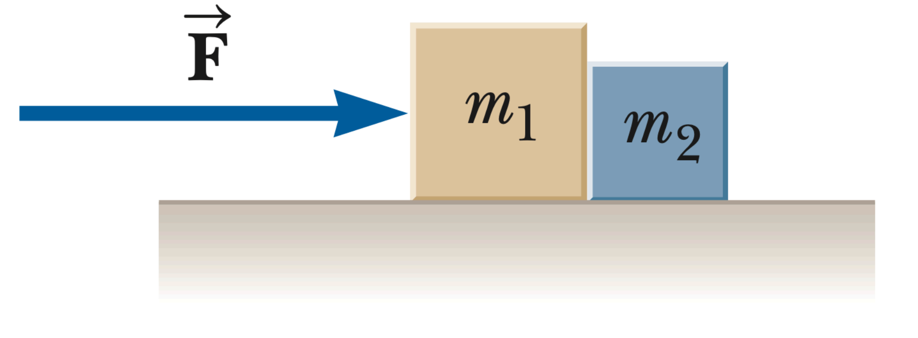
Example 5.6

Two blocks of masses m_1 and m_2, with $m_1 > m_2$, are placed in contact with each other on a frictionless, horizontal surface, as in the Figure. A constant horizontal force $\vec{F}$ is applied to m_1 as shown.



(A) Find the magnitude of the acceleration of the system.

(B) Determine the magnitude of the contact force between the two blocks.

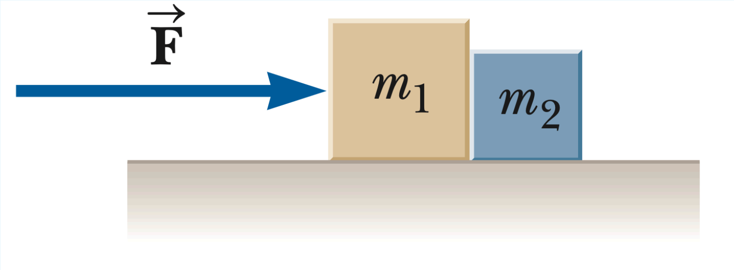
5.3 Examples

Solution 5.6

- (A) Since the blocks move together, they have the same acceleration a.
- The net force acting on the system is $\vec{F}$, and the total mass of the system is $m_1 + m_2$.
- Applying Newton's second law to the system gives:

$$\sum F_x = F = (m_1 + m_2)a_x$$

$$\Rightarrow a_x = \frac{F}{m_1 + m_2}$$



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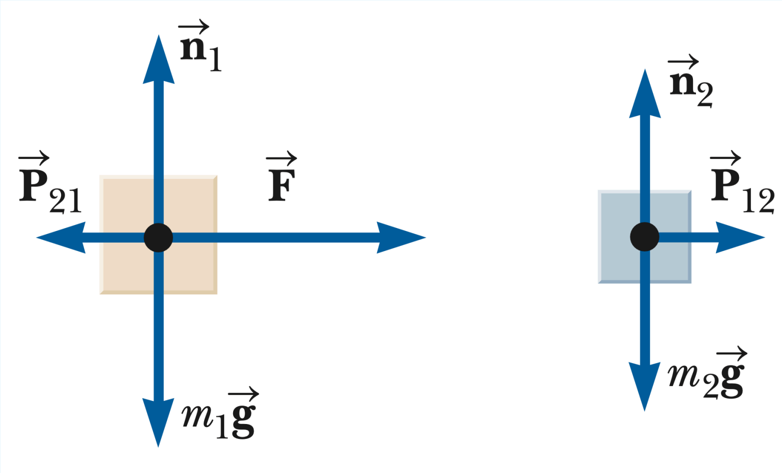
- (B) To find the contact force $\vec{P}_{12}$ between the two blocks, we consider only block m_2.
- The only horizontal force acting on block m_2 is the contact force $\vec{P}_{12}$.
- Applying Newton's second law to block m_2 gives:

$$P_{12} = m_2 a_x$$

$$\Rightarrow P_{12} = \left(\frac{m_2}{m_1 + m_2}\right) F$$

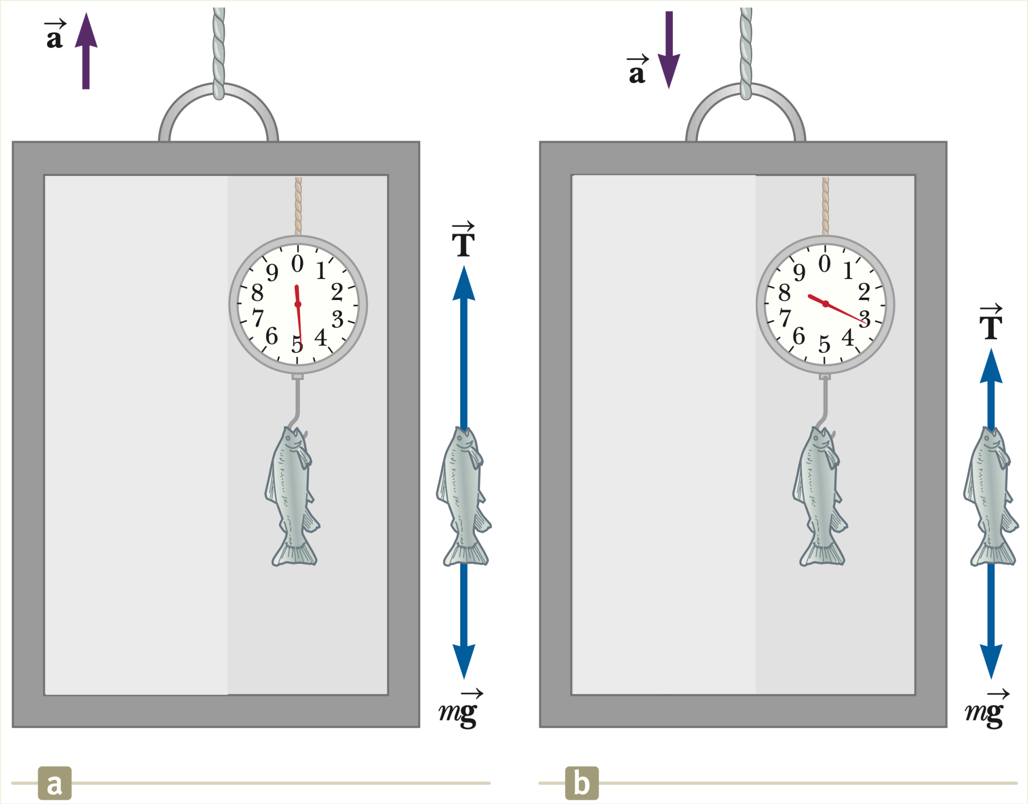
- From Newton's third law, $\vec{P}_{21} = -\vec{P}_{12}$.



5.3 Examples

Example 5.7

A fish of mass m on a spring scale attached to the ceiling of an elevator, as illustrated in the Figure. *Show* that if the elevator accelerates either upward or downward, the spring scale gives a reading that is different from the weight of the fish.



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Solution 5.7

- If the elevator is not accelerating, the reading of the spring scale is:

$$\sum F_y = T - F_g = 0$$

$$\Rightarrow T = F_g = mg$$

- If the elevator accelerates upward with acceleration a, the reading of the spring scale is:

$$\sum F_y = T - F_g = ma$$

$$\Rightarrow T = m(g + a)$$

Therefore, the reading of the spring scale is greater than the weight of the fish.

5.3 Examples

- If the elevator accelerates downward with acceleration a, the reading of the spring scale is:

$$\sum F_y = T - F_g = -ma$$
$$\Rightarrow T = m(g - a)$$

Therefore, the reading of the spring scale is less than the weight of the fish.

5.3 Examples

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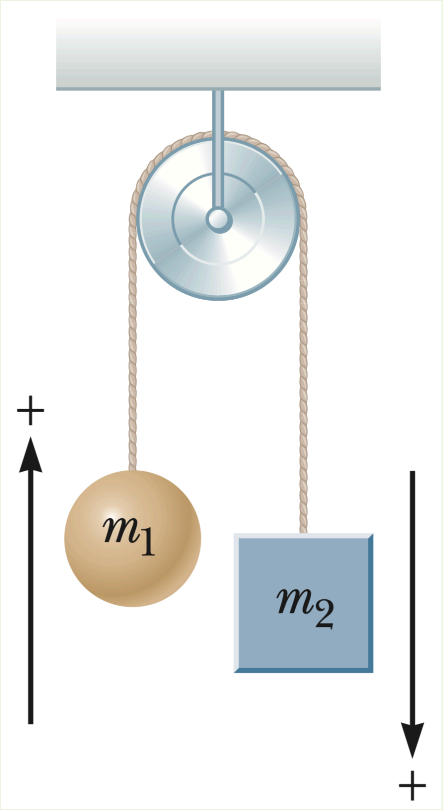
Example 5.8

When two objects of unequal mass are hung vertically over a frictionless pulley of negligible mass, as in the Figure, the arrangement is called an Atwood machine. The device is sometimes used in the laboratory to measure the free-fall acceleration.

Determine the magnitude of the *acceleration* of the two objects and the *tension* in the lightweight cord.



Solution 5.8

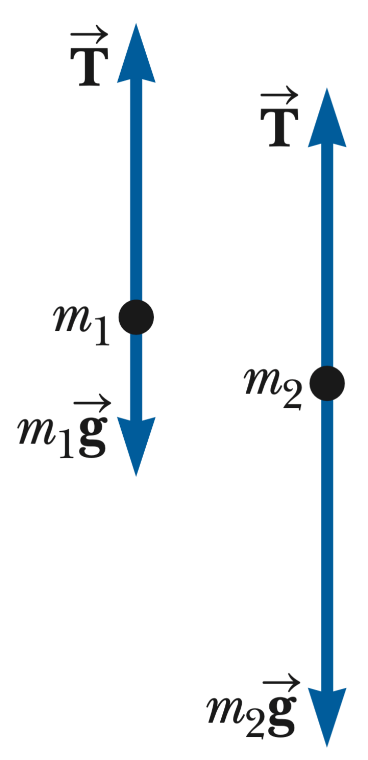
- We set the positive direction to be clockwise (upward for m_1 and downward for m_2).
- Applying Newton's second law to each mass:

$$\sum F_{1y} = T - m_1 g = m_1 a \qquad (1)$$

$$\sum F_{2y} = m_2 g - T = m_2 a \qquad (2)$$

- Adding these two equations eliminates T:

$$m_2 g - m_1 g = (m_1 + m_2) a$$



5.3 Examples

- Solving for a gives:

$$a = \left(\frac{m_2 - m_1}{m_1 + m_2}\right) g \tag{3}$$

- To find T, we substitute the value of a into Eq (1):

$$T = m_1 g + m_1 a = m_1 g + m_1 \left(\frac{m_2 - m_1}{m_1 + m_2}\right) g$$

- Simplifying gives:

$$T = \left(\frac{2m_1 m_2}{m_1 + m_2}\right) g \tag{4}$$

5.3 Examples

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Math Derivation

T from Eq (4) is derived as follows:

$$\begin{aligned}
T &= m_1 g + m_1 \left(\frac{m_2 - m_1}{m_1 + m_2}\right) g \\
&= m_1 g \left[1 + \left(\frac{m_2 - m_1}{m_1 + m_2}\right)\right] \\
&= m_1 g \left[\frac{m_1 + m_2}{m_1 + m_2} + \frac{m_2 - m_1}{m_1 + m_2}\right] \\
&= m_1 g \left[\frac{m_1 + m_2 + m_2 - m_1}{m_1 + m_2}\right] = m_1 g \left[\frac{2m_2}{m_1 + m_2}\right] \Longrightarrow \text{Eq (4)}
\end{aligned}$$

5.3 Examples

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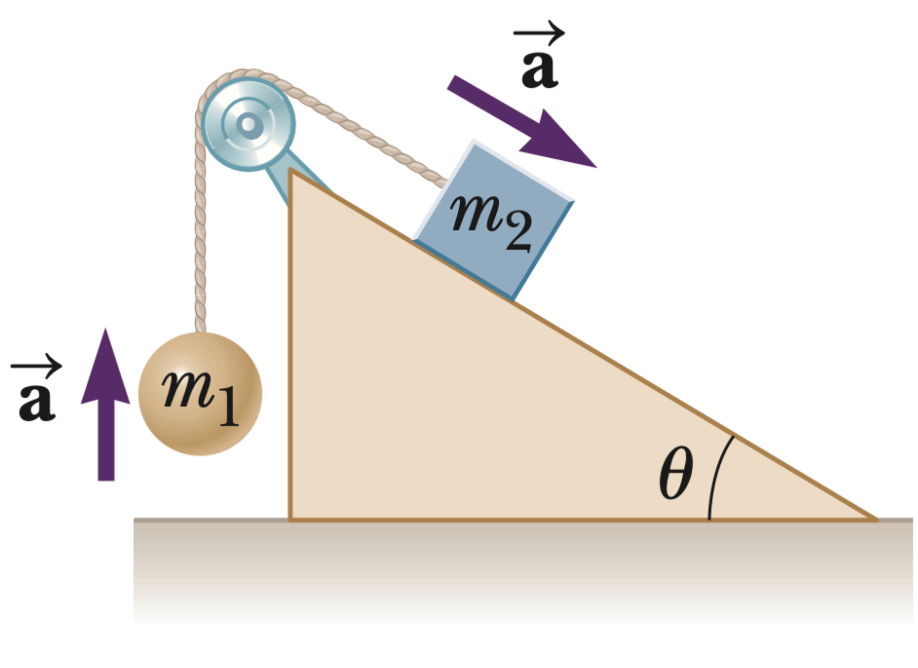
Example 5.9

A ball of mass m_1 and a block of mass m_2 are attached by a lightweight cord that passes over a frictionless pulley of negligible mass, as in the Figure. The block lies on a frictionless incline of angle θ.

Find the magnitude of the acceleration of the two objects and the tension in the cord.



5.3 Examples

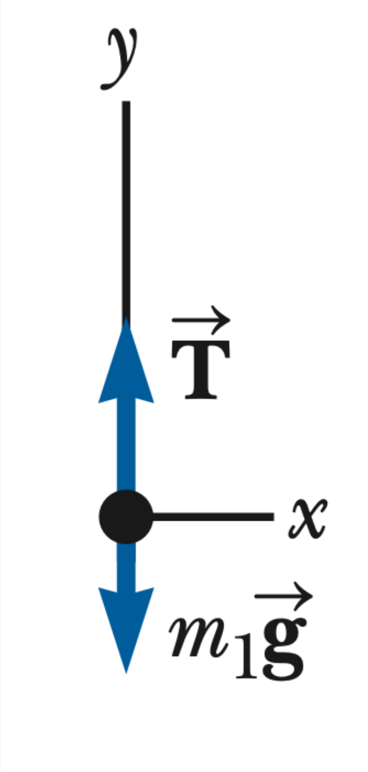
Solution 5.9

- We set the positive direction to be clockwise (upward for m_1 and down the incline for m_2).
- Applying Newton's second law to the first mass:

$$\sum F_y = m_1 a$$
$$T - m_1 g = m_1 a \tag{1}$$

- Therefore,

$$T = m_1 g + m_1 a \tag{2}$$

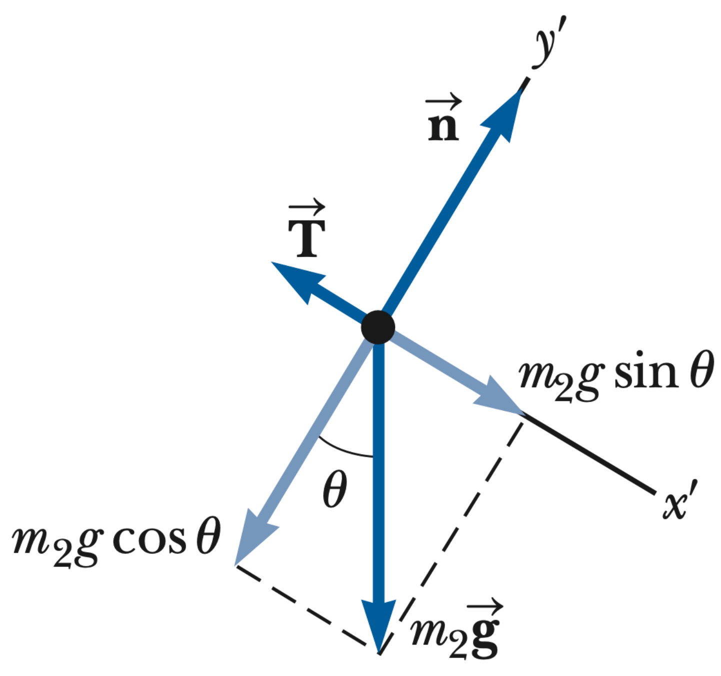


5.3 Examples

- Applying Newton's second law to m_2:

$$\sum F_{x'} = m_2 g \sin\theta - T = m_2 a \qquad (3)$$

$$\sum F_{y'} = n - m_2 g \cos\theta = 0$$



- To find a, we substitute the value of T from Eq (2) into Eq (3):

$$m_2 g \sin\theta - (m_1 g + m_1 a) = m_2 a$$

$$\Rightarrow (m_1 + m_2)a = m_2 g \sin\theta - m_1 g$$

5.3 Examples

$$a = \left(\frac{m_2 \sin\theta - m_1}{m_1 + m_2} \right) g \tag{4}$$

- To find T, we substitute the value of a into Eq (2):

$$T = m_1 g + m_1 \left(\frac{m_2 \sin\theta - m_1}{m_1 + m_2} \right) g$$

- Simplifying gives:

$$T = \left[\frac{m_1 m_2 (1 + \sin\theta)}{m_1 + m_2} \right] g$$

1. The Concept of Force

2. Newton’s First Law

3. Newton’s Second Law

4. Newton’s Third Law

5. Some Applications of Newton’s Laws

6. Forces of Friction

7. Suggested Problems

6.1 What is Friction?

- Friction is the resistance to the motion because the object interacts with its surroundings.
- We call such resistance a **force of friction**.
- Forces of friction are very important in our everyday lives.
- They allow us to walk or run and are necessary for the motion of wheeled vehicles.

There are two types of frictional forces:

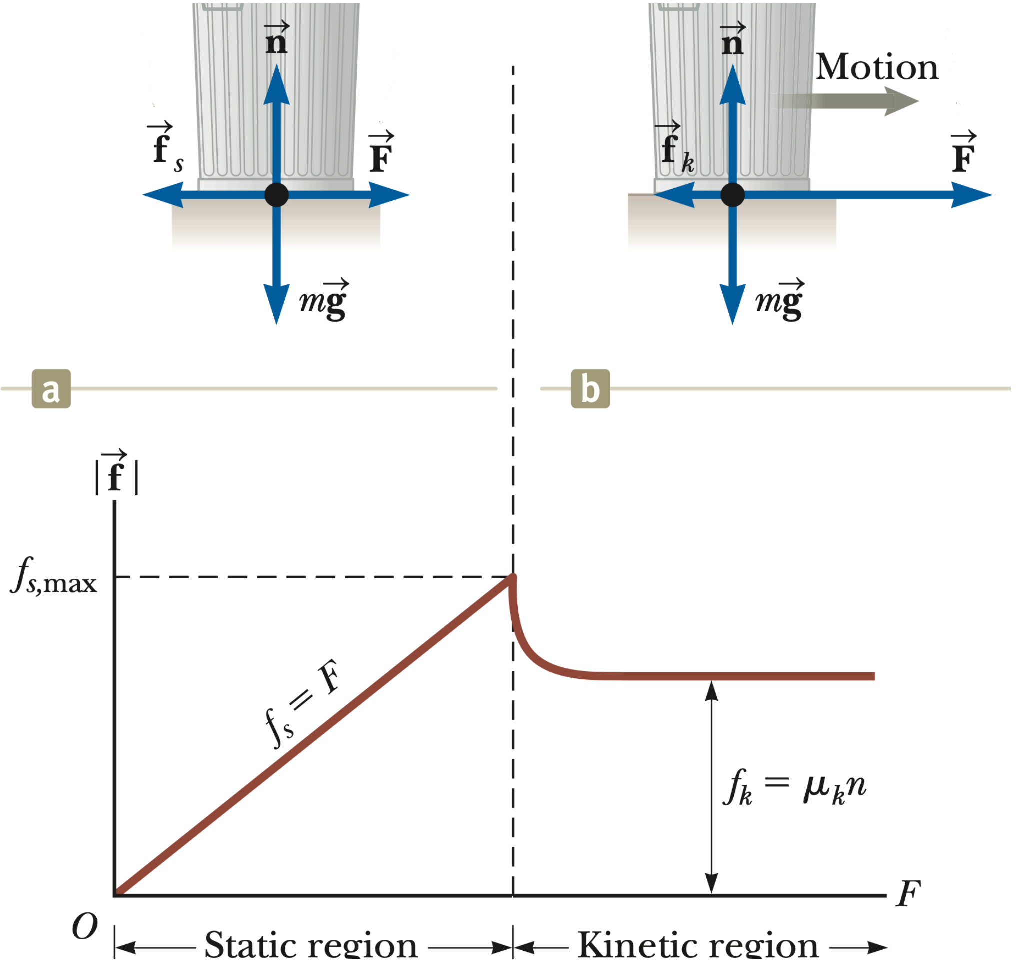
1. Force of static friction ($\vec{f}_s$)
2. Force of kinetic friction ($\vec{f}_k$)

6.2 Force of Static Friction ($\vec{f}_s$)

- Static friction acts on an object when it is NOT moving.
- It is proportional to the applied force $\vec{F}$ up to a maximum value $\vec{f}_{s,\,\mathrm{max}}$ beyond which the object starts to move.
- The maximum static friction is:

$$f_{s,\,\mathrm{max}} = \mu_s n$$

where μ_s is the coefficient of static friction, and n is the normal force.

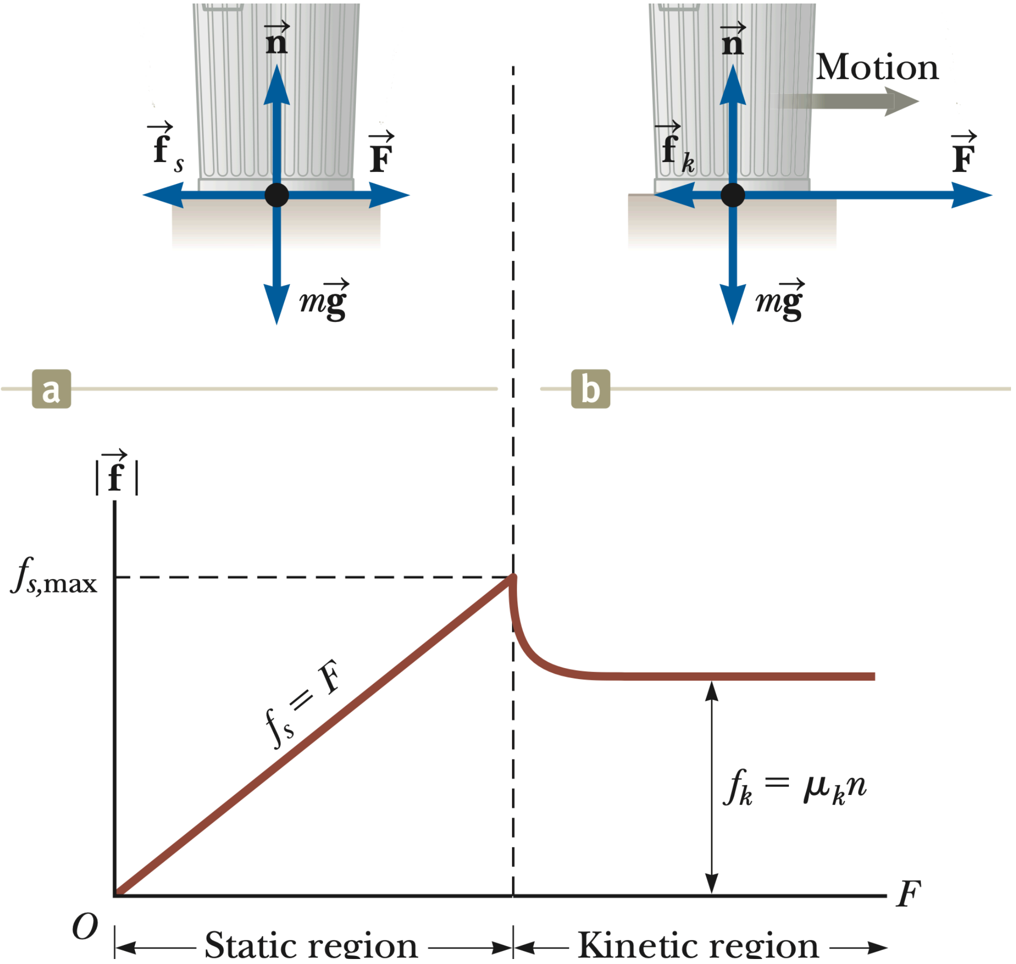


6.3 Force of Kinetic Friction ($\vec{f}_k$)

- Kinetic friction acts on an object when it is moving.
- It is roughly constant and independent of the applied force $\vec{F}$.
- The kinetic friction is:

$$f_k = \mu_k n$$

where μ_k is the coefficient of kinetic friction, and n is the normal force.



6.4 coefficients of Friction

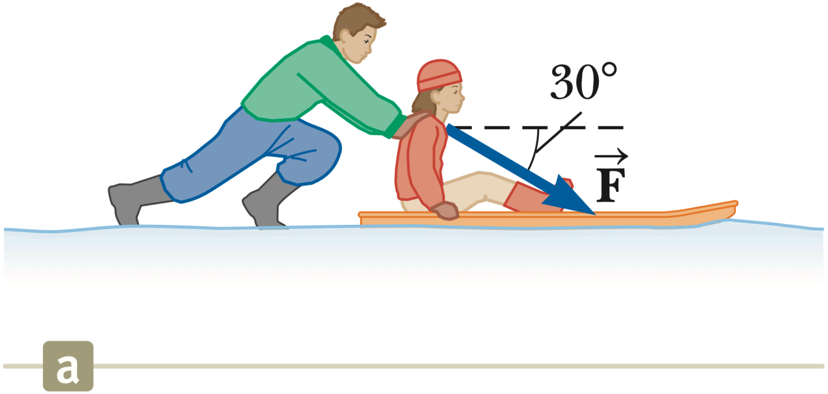
- The coefficients of friction depend on the materials in contact.
- Typical values of μ_s are larger than those of μ_k for the same materials.

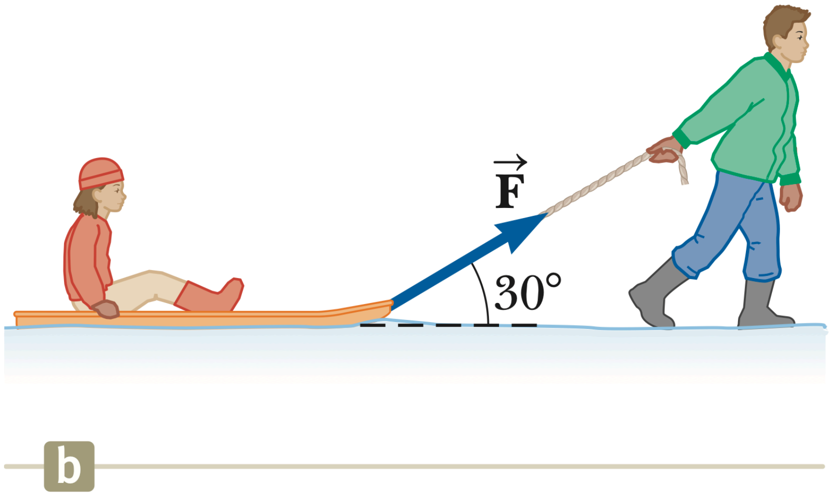
TABLE 5.1 Coefficients of Friction

	μ_s	μ_k
Rubber on concrete	1.0	0.8
Steel on steel	0.74	0.57
Aluminum on steel	0.61	0.47
Glass on glass	0.94	0.4
Copper on steel	0.53	0.36
Wood on wood	0.25–0.5	0.2
Waxed wood on wet snow	0.14	0.1
Waxed wood on dry snow	—	0.04
Metal on metal (lubricated)	0.15	0.06
Teflon on Teflon	0.04	0.04
Ice on ice	0.1	0.03
Synovial joints in humans	0.01	0.003

Note: All values are approximate. In some cases, the coefficient of friction can exceed 1.0.

6.5 How to Reduce Friction?!

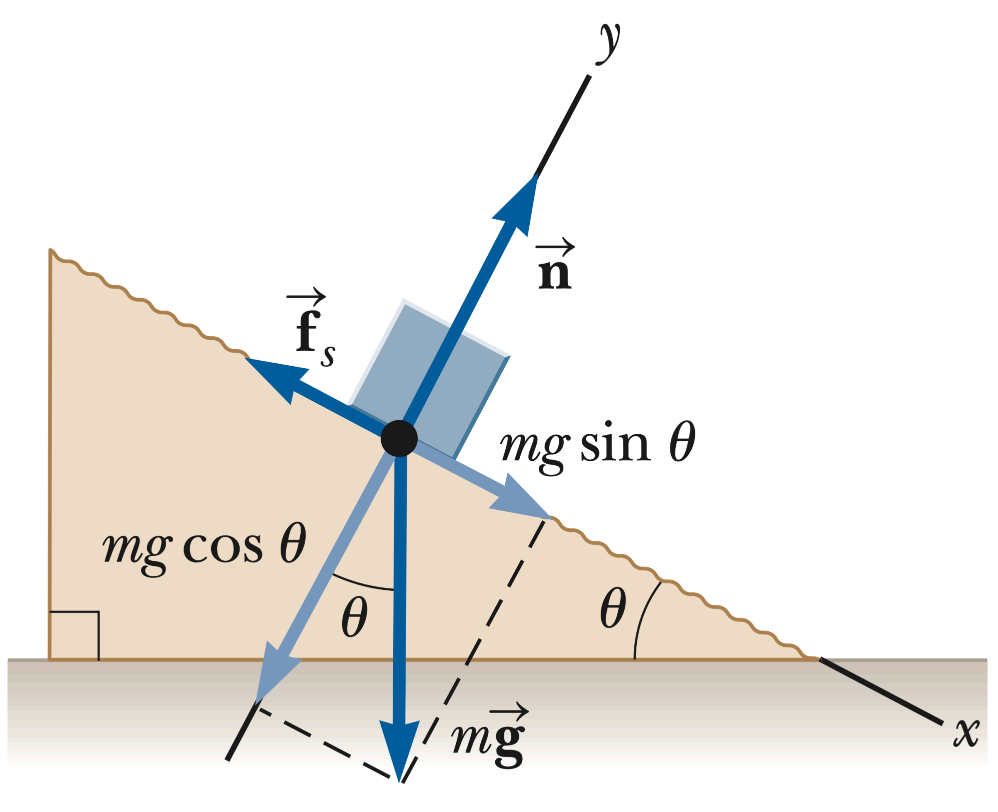




Example 6.10

The following is a simple method of measuring coefficients of friction. Suppose a block is placed on a rough surface inclined relative to the horizontal as shown in the Figure. The incline angle is increased until the block starts to move.

Show that you can obtain μ_s by measuring the critical angle θ_c at which this slipping just occurs.



6.6 Example

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Solution 6.10

$$\sum F_x = ma$$

$$mg\sin\theta_c - f_s = 0$$

$$\implies f_s = mg\sin\theta_c \qquad (1)$$

$$\sum F_y = n - mg\cos\theta_c = 0$$

$$\implies n = mg\cos\theta_c \qquad (2)$$

- Therefore,

$$\frac{f_s}{n} = \tan\theta_c$$

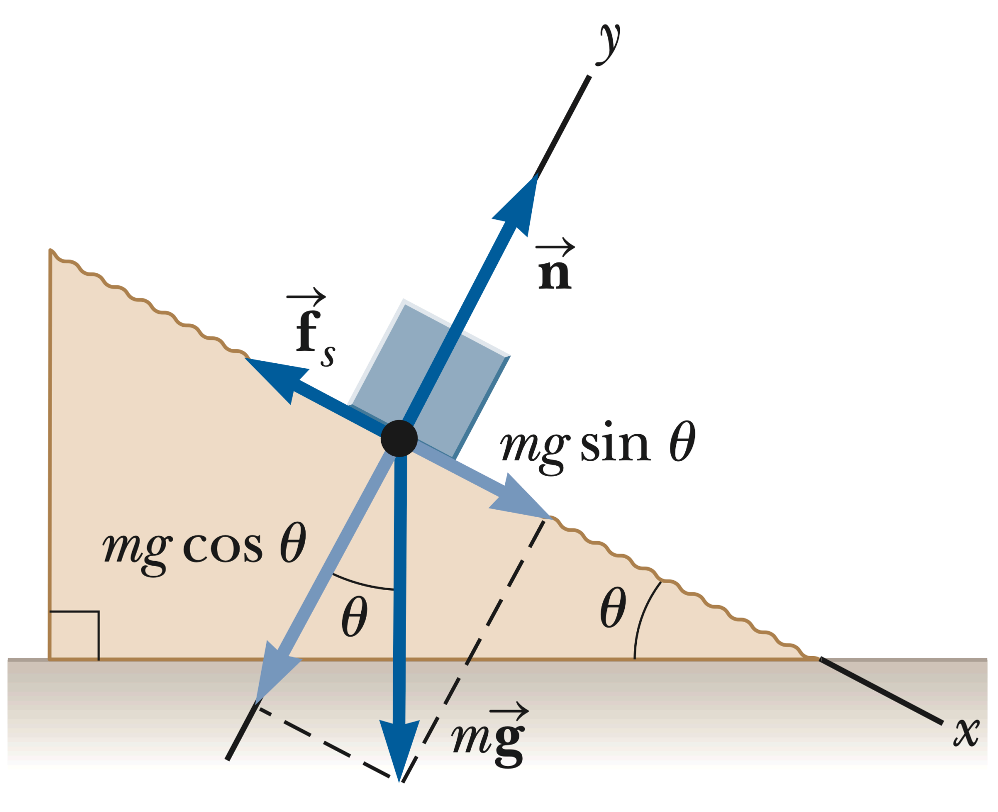
- Using ($f_s = \mu_s n$), we get

$$\mu_s = \tan\theta_c$$

6.6 Example

For example, if the block starts to slip when $\theta_c = 20°$, then

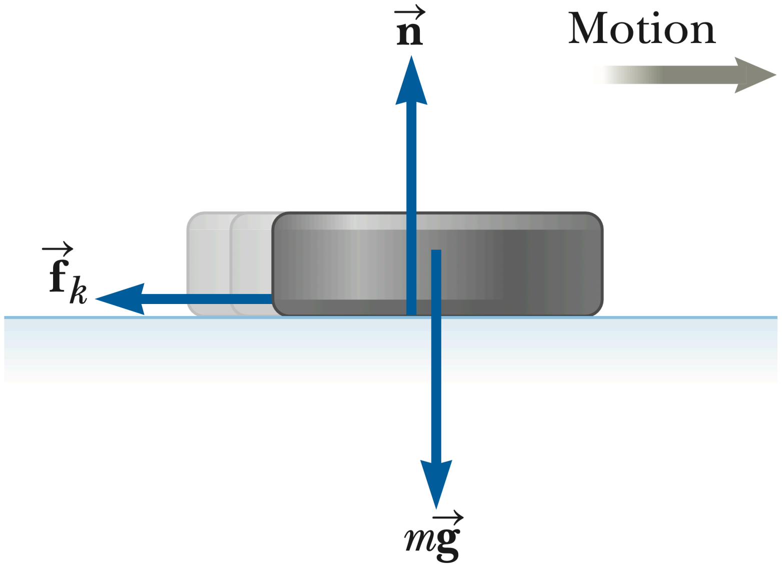
$$\mu_s = \tan 20° = 0.364$$



6.6 Example

Example 6.11

A hockey puck on a frozen pond (بركة ماء) is given an initial speed of 20 m/s. If the puck always remains on the ice and slides 115 m before coming to rest, *determine* the coefficient of kinetic friction between the puck and ice.



6.6 Example

Solution 6.11

- Applying Newton's second law to the puck:

$$\sum F_y = n - mg = 0$$
$$\Rightarrow n = mg$$

- The only horizontal force acting on the puck is the kinetic friction $\vec{\boldsymbol{f}}_k$:

$$\sum F_x = -f_k = ma_x$$
$$\Rightarrow a_x = -\frac{f_k}{m} = -\frac{\mu_k n}{m} = -\frac{\mu_k mg}{m} = -\mu_k g$$

6.6 Example

- Using the fourth equation of motion:

$$v_f^2 = v_i^2 + 2a_x(x_f - x_i)$$

- Since $v_f = 0$, $x_i = 0$, and using $a_x = -\mu_k g$, we have:

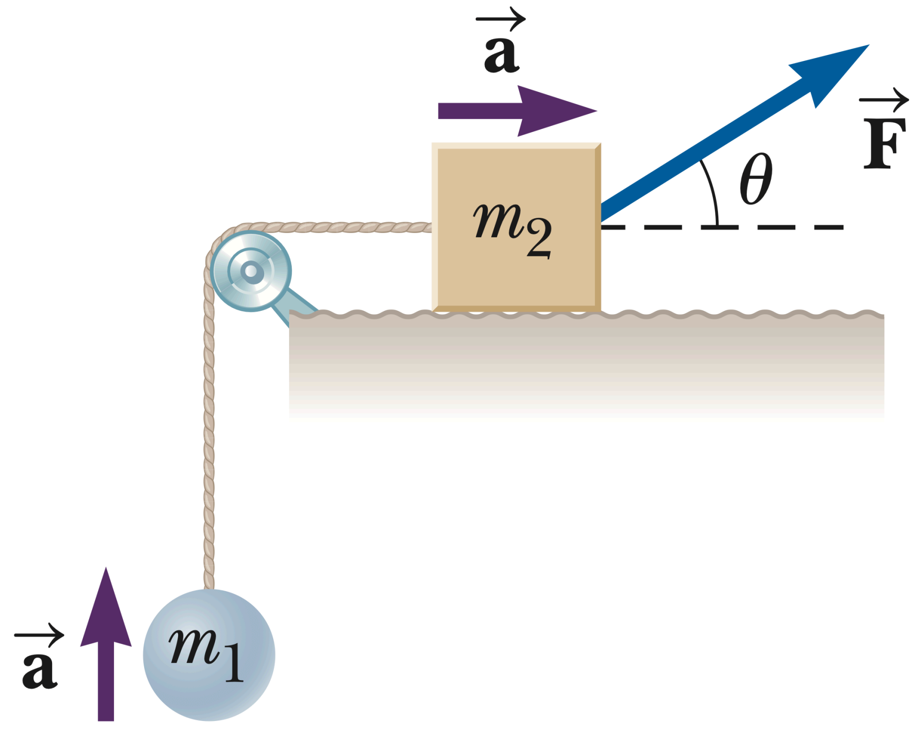
$$0 = v_i^2 - 2\mu_k g x_f$$

$$\Rightarrow \mu_k = \frac{v_i^2}{2gx_f} = \frac{20^2}{2(9.8)(115)} = 0.177$$

6.6 Example

Example 6.12

A block of mass m_2 on a rough, horizontal surface is connected to a ball of mass m_1 by a lightweight cord over a lightweight, frictionless pulley, as shown in the Figure. A force of magnitude F at an angle θ with the horizontal is applied to the block as shown. The coefficient of kinetic friction between the block and surface is μ_k. *Determine* the magnitude of the acceleration of the two objects.



6.6 Example

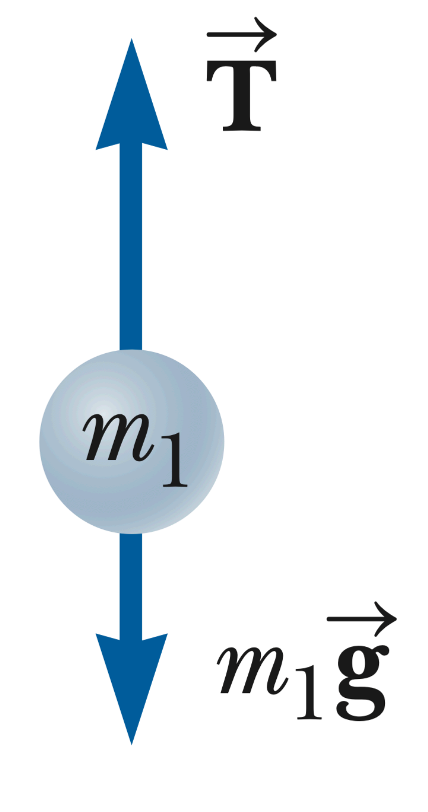
Solution 6.12

- We set the positive direction to be clockwise.
- Applying Newton's second law to m_1:

$$\sum F_{1y} = T - m_1 g = m_1 a \qquad (1)$$

- Therefore,

$$\begin{aligned} T &= m_1 g + m_1 a \\ &= m_1 (g + a) \end{aligned} \qquad (2)$$



6.6 Example

- Applying Newton's second law to m_2:

$$\sum F_{2y} = n + F\sin\theta - m_2 g = 0 \quad (3)$$

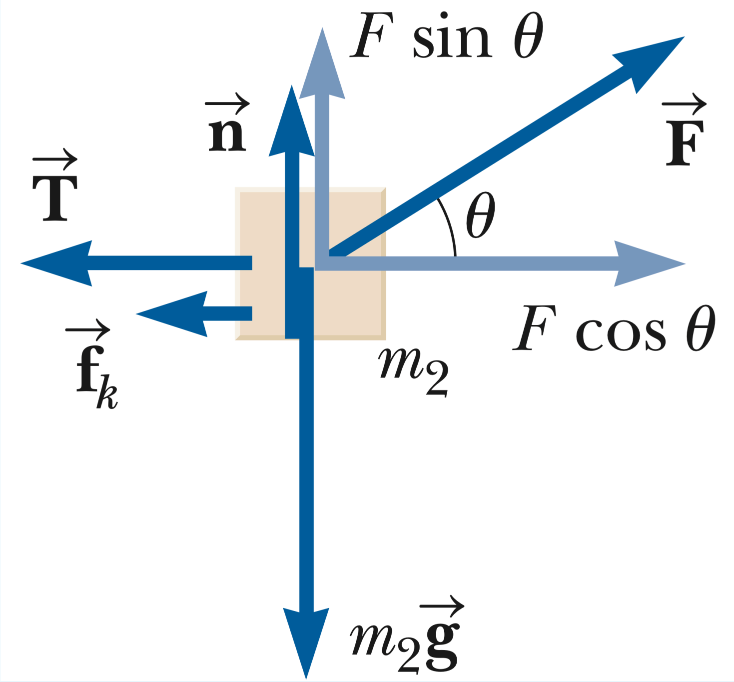
$$\Longrightarrow n = m_2 g - F\sin\theta \quad (4)$$

$$\sum F_{2x} = F\cos\theta - T - f_k = m_2 a \quad (5)$$

$$\Longrightarrow m_2 a = F\cos\theta - T - (\mu_k \mathrm{n})$$

$$= F\cos\theta - (m_1 g + m_1 a) \quad (6)$$

$$-\mu_k (m_2 g - F\sin\theta)$$



6.6 Example

$$m_2 a + m_1 a = F\cos\theta - m_1 g - \mu_k m_2 g + \mu_k F \sin\theta$$

$$(m_1 + m_2)a = F(\cos\theta + \mu_k \sin\theta) - (m_1 + \mu_k m_2)g$$

- Solving for a gives:

$$a = \frac{F(\cos\theta + \mu_k \sin\theta) - (m_1 + \mu_k m_2)g}{m_1 + m_2} \tag{7}$$

- Note: If a is negative, then the direction of the kinetic friction f_k in Eq (5) has to be reversed, to be opposite to the direction of motion.
  Therefore, $\mu_k \Longrightarrow -\mu_k$ in Eq (7).

7. Suggested Problems

3, 7, 11, 16, 18, 24, 25, 26, 28, 30, 31, 37, 41, 44, 45, 46, 68

Problem 7.1

A car is traveling at 50.0 mi/h on a horizontal highway.
(a) If the coefficient of static friction between road and tires on a rainy day is 0.1, what is the minimum distance in which the car will stop?
(b) What is the stopping distance when the surface is dry and $\mu_s = 0.6$?

Solution 7.12

(a)

- From Newton's second law to the car:

$$\sum F_y = n - mg = 0$$
$$\Rightarrow n = mg$$

- The maximum static friction is:

$$f_{s,\,\max} = \mu_s n = \mu_s mg$$

- Applying Newton's second law in the x direction:

$$\sum F_x = -f_{s,\,\max} = ma_x$$

- Therefore,

$$\Rightarrow a_x = -\frac{f_{s,\,\mathrm{max}}}{m} = -\mu_s g$$

- Using the fourth equation of motion:

$$v_f^2 = v_i^2 + 2a_x\left(x_f - x_i\right)$$

- Since $v_f = 0$, $x_i = 0$, and using $a_x = -\mu_s g$, we have:

$$0 = v_i^2 - 2\mu_s g x_f$$

$$\Rightarrow x_f = \frac{v_i^2}{2\mu_s g}$$

- Converting 50 mi/h to m/s gives 22.4 m/s. Therefore,

$$x_f = \frac{22.4^2}{2(0.1)(9.8)} = 256 \text{ m}$$

(b) For $\mu_s = 0.6$,

$$x_f = \frac{22.4^2}{2(0.6)(9.8)} = 42.7 \text{ m}$$