Chapter 5

The Laws of Motion

The Laws of Motion

The description of an object in motion included its position, velocity, and acceleration.

There was no consideration of what might influence that motion.

Two main factors need to be addressed to answer questions about why the motion of an object will change.

- Forces acting on the object
- The mass of the object

Dynamics studies the causes of motion.

Will start with three basic laws of motion

- Formulated by Sir Isaac Newton

Force

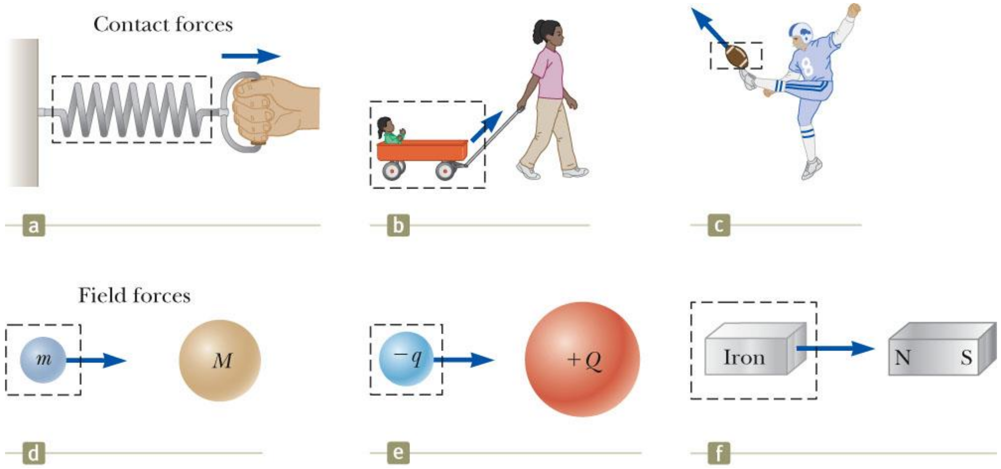
Forces in everyday experience

- Push on an object to move it
- Throw or kick a ball
- May push on an object and not be able to move it

Forces are what cause any change in the velocity of an object.

- Newton's definition
- A force is that which causes an acceleration

Classes of Forces



Contact forces involve physical contact between two objects

- Examples a, b, c

Field forces act through empty space

- No physical contact is required
- Examples d, e, f

Fundamental Forces

Gravitational force

- Between objects

Electromagnetic forces

- Between electric charges

Nuclear force

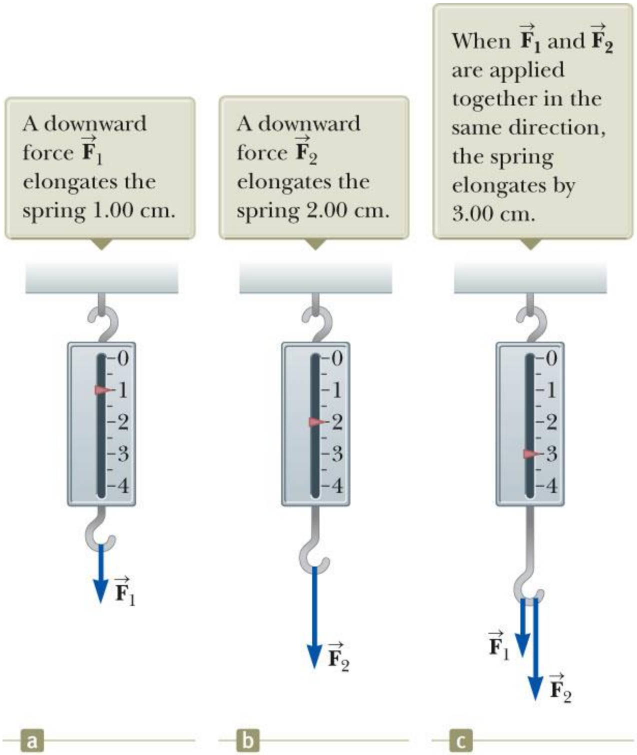
- Between subatomic particles

Weak forces

- Arise in certain radioactive decay processes

Note: These are all field forces.

More About Forces



A spring can be used to calibrate the magnitude of a force.

Doubling the force causes double the reading on the spring.

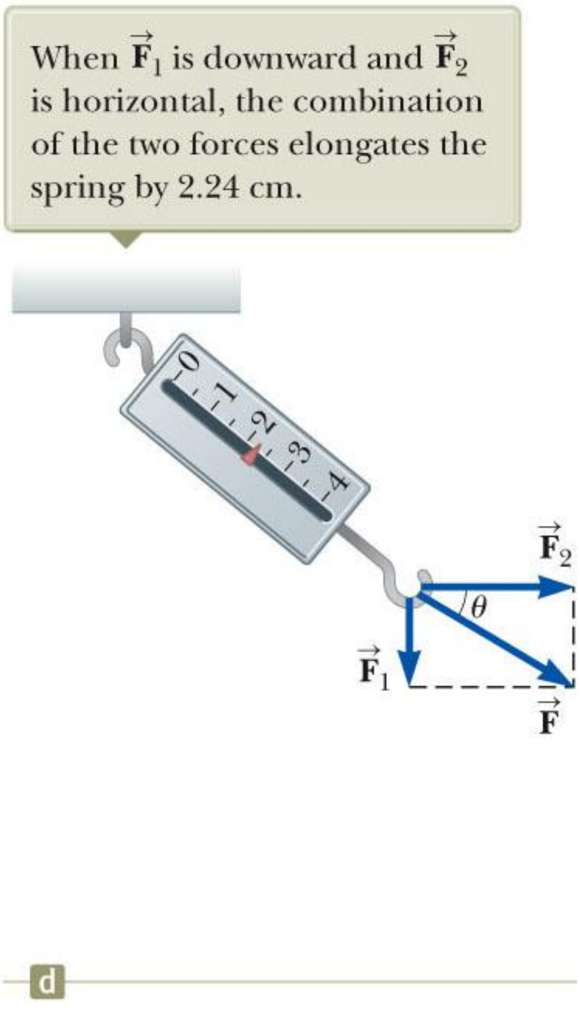
When both forces are applied, the reading is three times the initial reading.

Vector Nature of Forces

The forces are applied perpendicularly to each other.

The resultant (or net) force is the hypotenuse.

Forces are vectors, so you must use the rules for vector addition to find the net force acting on an object.



Newton's First Law

If an object does not interact with other objects, it is possible to identify a reference frame in which the object has zero acceleration.

- This is also called the *law of inertia.*
- It defines a special set of reference frames called *inertial frames.*
  - We call this an ***inertial frame of reference.***

Newton's First Law – Alternative Statement

In the absence of external forces, when viewed from an inertial reference frame, an object at rest remains at rest and an object in motion continues in motion with a constant velocity.

- Newton's First Law describes what happens in the absence of a force.
  - Does not describe zero net force
- Also tells us that when no force acts on an object, the acceleration of the object is zero
- Can conclude that any isolated object is either at rest or moving at a constant velocity

The First Law also allows the definition of ***force*** as ***that which causes a change in the motion of an object.***

Inertia and Mass

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

Mass is that property of an object that specifies how much resistance an object exhibits to changes in its velocity.

Masses can be defined in terms of the accelerations produced by a given force acting on them:

$$m_1 / m_2 \equiv a_2 / a_1$$

- The magnitude of the acceleration acting on an object is inversely proportional to its mass.

More About Mass

Mass is an inherent property of an object.

Mass is independent of the object's surroundings.

Mass is independent of the method used to measure it.

Mass is a scalar quantity.

- Obeys the rules of ordinary arithmetic

The SI unit of mass is kg.

Mass vs. Weight

Mass and weight are two different quantities.

Weight is equal to the magnitude of the gravitational force exerted on the object.

- Weight will vary with location.

Example:

- w_{earth} = 180 lb; w_{moon} ~ 30 lb
- m_{earth} = 2 kg; m_{moon} = 2 kg

Newton's Second Law

When viewed from an inertial reference frame, the acceleration of an object is directly proportional to the net force acting on it and inversely proportional to its mass.

- Force is the cause of *changes* in motion, as measured by the acceleration.
  - Remember, an object can have motion in the absence of forces.
  - Do not interpret force as the cause of motion.

Algebraically,

$$\vec{\mathbf{a}} \propto \frac{\sum \vec{\mathbf{F}}}{m} \rightarrow \sum \vec{\mathbf{F}} = m\vec{\mathbf{a}}$$

- With a proportionality constant of 1 and speeds much lower than the speed of light.

More About Newton’s Second Law

$\sum \vec{\mathbf{F}}$ is the net force

- This is the vector sum of all the forces acting on the object.
  - May also be called the total force, resultant force, or the unbalanced force.

Newton’s Second Law can be expressed in terms of components:

- $\Sigma F_x = m\, a_x$
- $\Sigma F_y = m\, a_y$
- $\Sigma F_z = m\, a_z$

Remember that ma is not a force.

- The sum of the forces is equated to this product of the mass of the object and its acceleration.

Units of Force

The SI unit of force is the **newton** (N).

- $1\ N = 1\ kg \cdot m / s^2$

The US Customary unit of force is a **pound** (lb).

- $1\ lb = 1\ slug \cdot ft / s^2$

1 N ~ ¼ lb

Gravitational Force

The gravitational force, $\vec{\mathbf{F}}_g$, is the force that the earth exerts on an object.

This force is directed toward the center of the earth.

From Newton's Second Law:

- $\vec{\mathbf{F}}_g = m\vec{\mathbf{g}}$

Its magnitude is called the weight of the object.

- Weight = $F_g = mg$

More About Weight

Because it is dependent on *g*, the weight varies with location.

- *g*, and therefore the weight, is less at higher altitudes.
- This can be extended to other planets, but the value of g varies from planet to planet, so the object's weight will vary from planet to planet.

Weight is not an inherent property of the object.

- The weight is a property of a *system* of items: the object and the Earth.

Note about units:

- Kilogram is **not** a unit of weight.
- 1 kg = 2.2 lb is an equivalence valid only on the Earth's surface.

Newton's Third Law

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

- $\vec{\mathbf{F}}_{12} = -\vec{\mathbf{F}}_{21}$
- Note on notation: $\vec{\mathbf{F}}_{AB}$ is the force exerted *by* A *on* B.

Newton’s Third Law, Alternative Statement

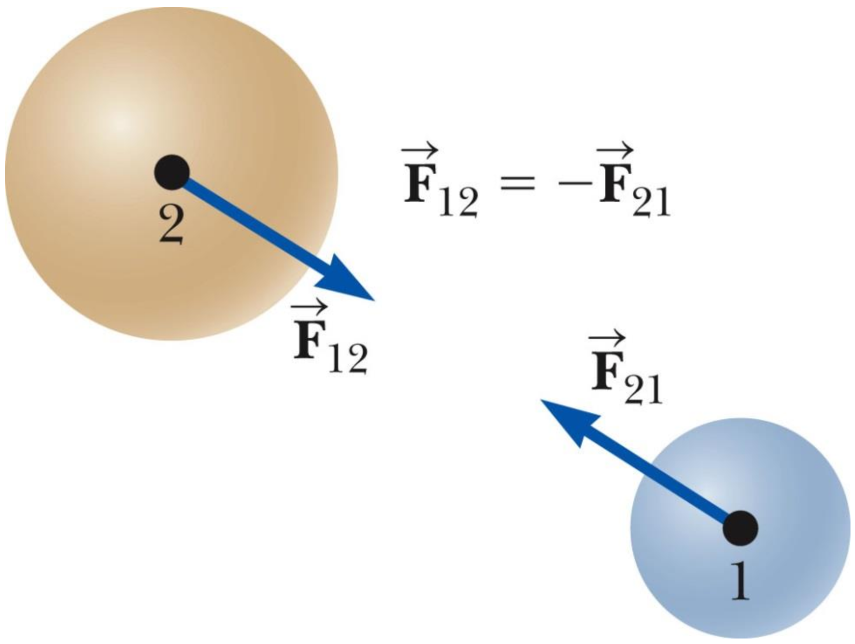
The action force is equal in magnitude to the reaction force and opposite in direction.

- One of the forces is the action force, the other is the reaction force.
- It doesn’t matter which is considered the action and which the reaction.
- The action and reaction forces must act on different objects and be of the same type.

Action-Reaction Examples, 1

The force $\vec{\mathbf{F}}_{12}$ exerted by object 1 on object 2 is equal in magnitude and opposite in direction to $\vec{\mathbf{F}}_{21}$ exerted by object 2 on object 1.

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

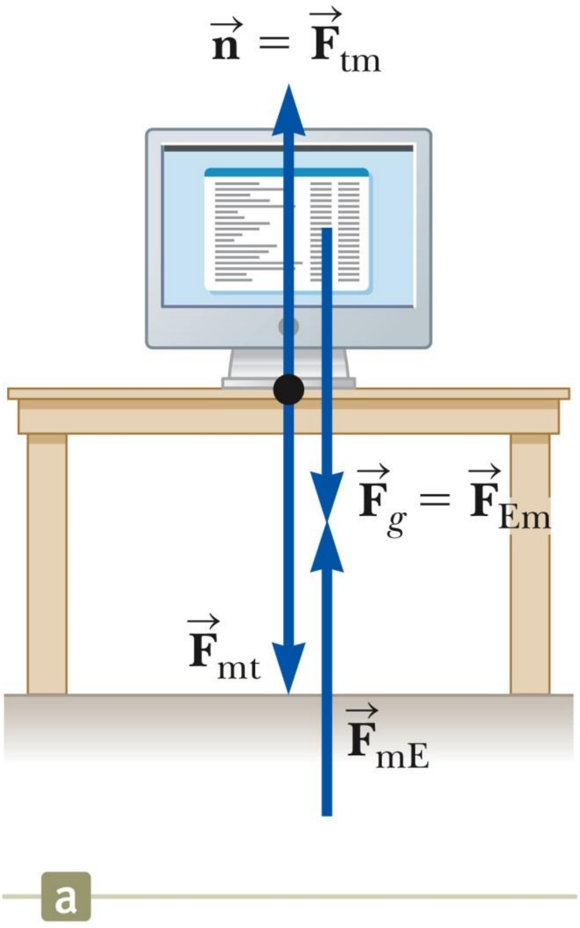


Action-Reaction Examples, 2

The normal force (table on monitor) is the reaction of the force the monitor exerts on the table.

- Normal means perpendicular, in this case

The action (Earth on monitor) force is equal in magnitude and opposite in direction to the reaction force, the force the monitor exerts on the Earth.

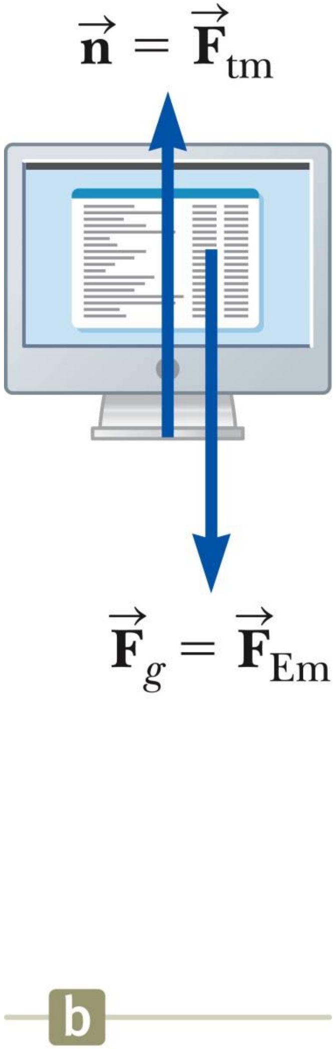


Forces on the Object

In a free body diagram, you want the forces acting on a particular object.

- Model the object as a particle

The normal force and the force of gravity are the forces that act on the monitor.



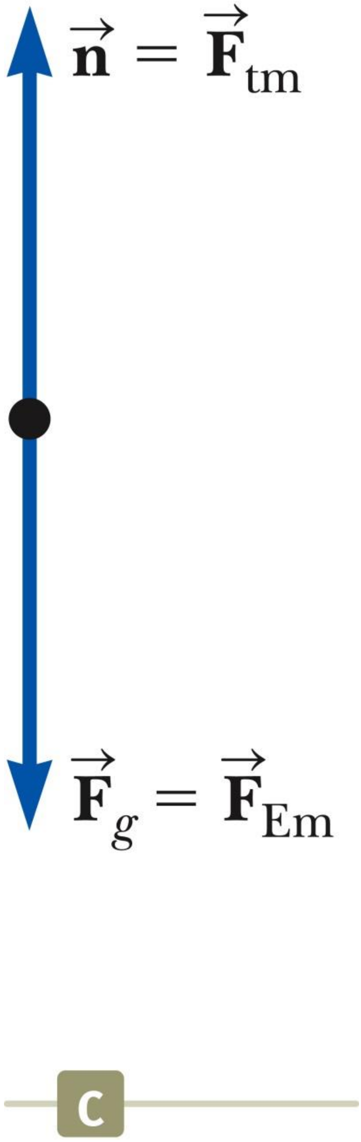
Free Body Diagram

The most important step in solving problems involving Newton's Laws is to draw the free body diagram.

Be sure to include only the forces acting on the object of interest.

Include any field forces acting on the object.

Do not assume the normal force equals the weight.



Free Body Diagrams and the Particle Model

The particle model is used by representing the object as a dot in the free body diagram.

The forces that act on the object are shown as being applied to the dot.

The free body helps isolate only those forces acting on the object and eliminate the other forces from the analysis.

Analysis Models Using Newton's Second Law

Assumptions

- Objects can be modeled as particles.
- Interested only in the external forces acting on the object
  - Can neglect reaction forces
- Initially dealing with frictionless surfaces
- Masses of strings or ropes are negligible.
  - The force the rope exerts is away from the object and parallel to the rope.
  - When a rope attached to an object is pulling it, the magnitude of that force is the **tension** in the rope.

Analysis Model: The Particle in Equilibrium

If the acceleration of an object that can be modeled as a particle is zero, the object is said to be in **equilibrium.**

- The model is the *particle in equilibrium model.*

Mathematically, the net force acting on the object is zero.

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

$$\sum F_x = 0 \text{ and } \sum F_y = 0$$

Equilibrium, Example

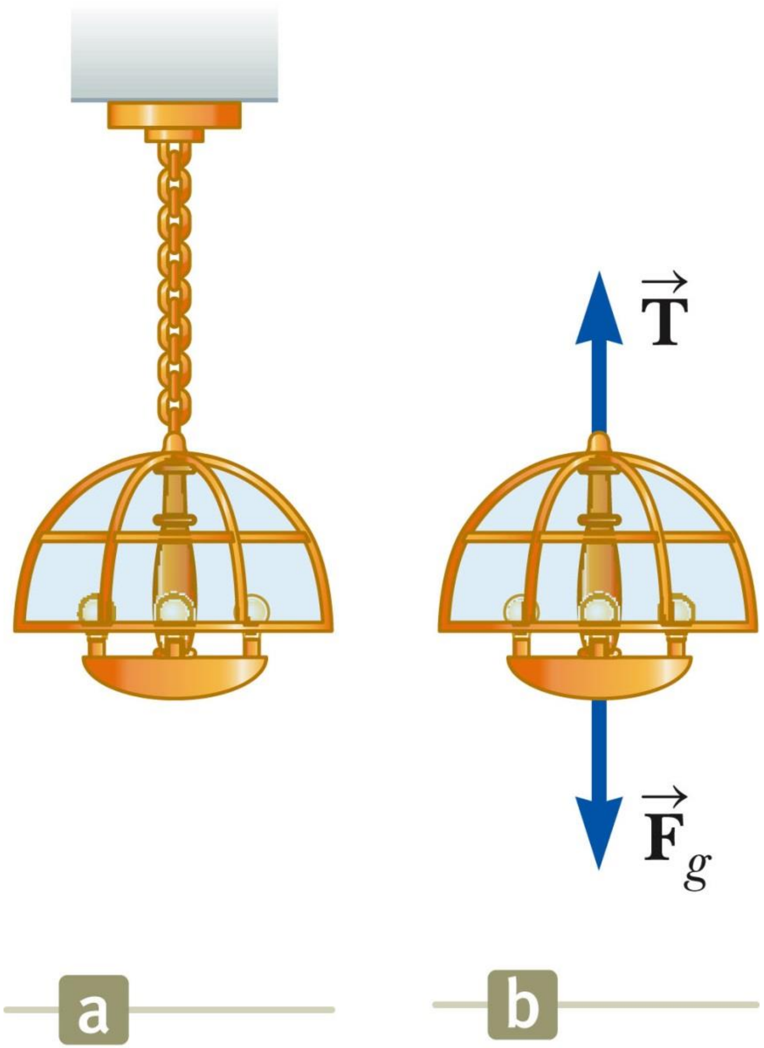
A lamp is suspended from a chain of negligible mass.

The forces acting on the lamp are:

- the downward force of gravity
- the upward tension in the chain

Applying equilibrium gives

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



Analysis Model: The Particle Under a Net Force

If an object that can be modeled as a particle experiences an acceleration, there must be a nonzero net force acting on it.

- Model is *particle under a net force model* .

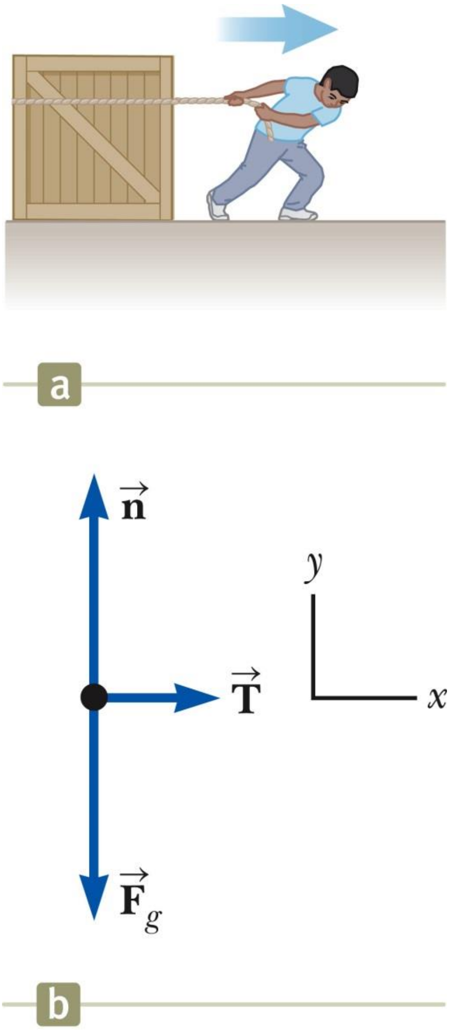
Draw a free-body diagram.

Apply Newton's Second Law in component form.

Newton's Second Law, Example 1

Forces acting on the crate:

- A tension, acting through the rope, is the magnitude of force $\vec{\mathbf{T}}$
- The gravitational force, $\vec{\mathbf{F}}_g$
- The normal force, $\vec{\mathbf{n}}$, exerted by the floor



Newton's Second Law, Example 1, cont.

Apply Newton's Second Law in component form:

$$\sum F_x = T = ma_x$$

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

Solve for the unknown(s)

If the tension is constant, then *a* is constant and the kinematic equations can be used to more fully describe the motion of the crate.

Note About the Normal Force

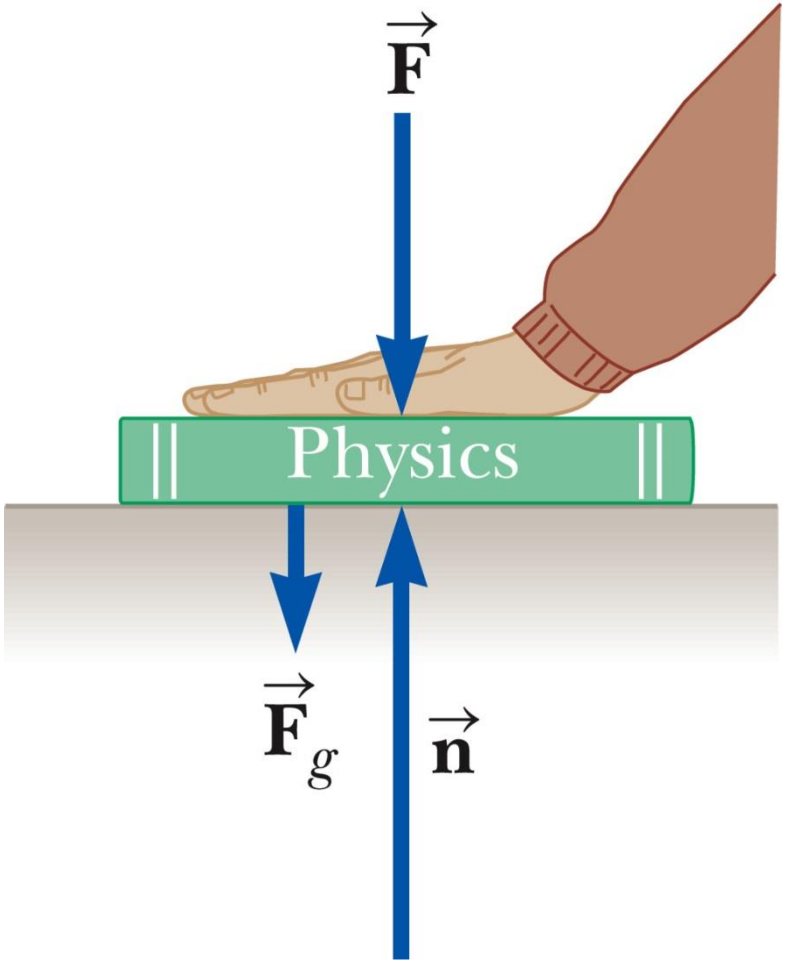
The normal force is **not** always equal to the gravitational force of the object.

For example, in this case

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

and $n = mg + F$

$\vec{\mathbf{n}}$ may also be less than $\vec{\mathbf{F}}_g$



Problem-Solving Hints – Applying Newton's Laws

Conceptualize

- Draw a diagram
- Choose a convenient coordinate system for each object

Categorize

- Is the model a particle in equilibrium?
  - If so, $\Sigma F = 0$
- Is the model a particle under a net force?
  - If so, $\Sigma F = m\,a$

Problem-Solving Hints – Applying Newton's Laws, cont.

Analyze

- Draw free-body diagrams for each object
- Include only forces acting on the object
- Find components along the coordinate axes
- Be sure units are consistent
- Apply the appropriate equation(s) in component form
- Solve for the unknown(s)

Finalize

- Check your results for consistency with your free-body diagram
- Check extreme values

Equilibrium, Example 2

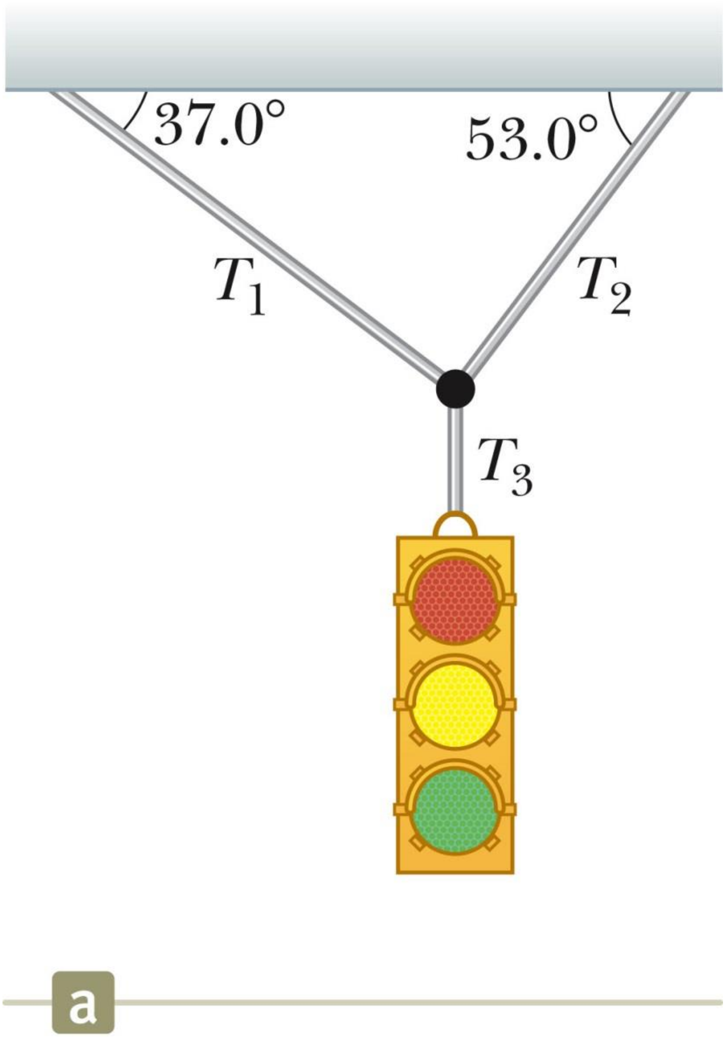
Example 5.4

Conceptualize the traffic light

- Assume cables don't break
- Nothing is moving

Categorize as an equilibrium problem

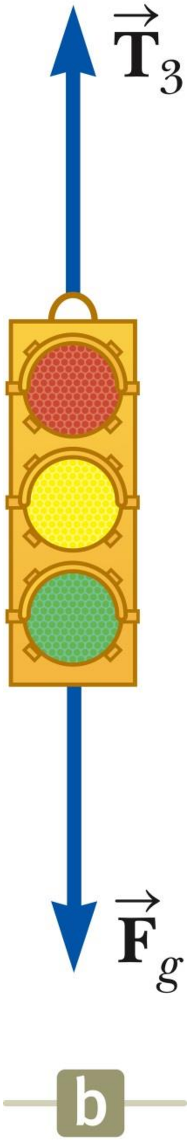
- No movement, so acceleration is zero
- Model as a particle in equilibrium

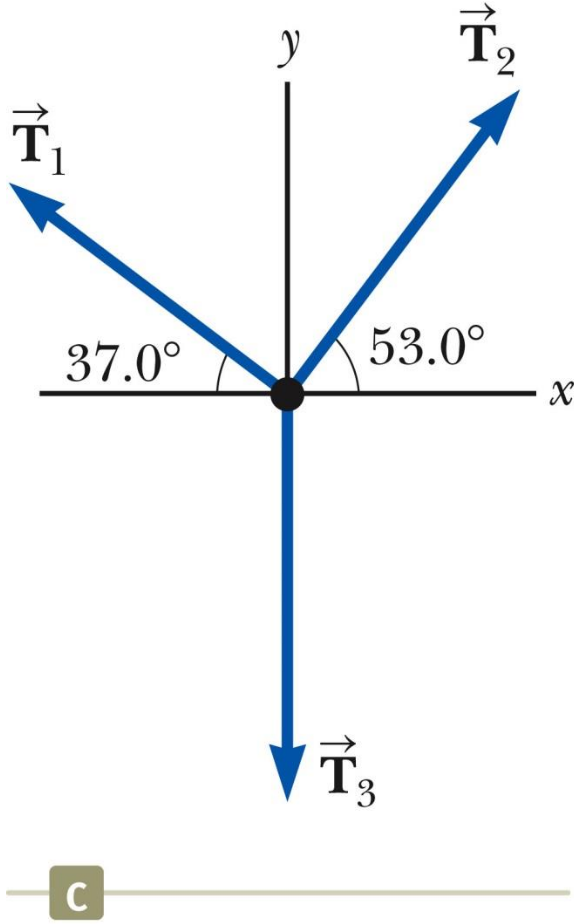


Equilibrium, Example 2, cont.

Analyze

- Construct a diagram for the forces acting on the light
- Construct a free body diagram for the knot where the three cables are joined
  - The knot is a convenient point to choose since all the forces of interest act along lines passing through the knot.
- Apply equilibrium equations to the knot





Equilibrium, Example 2, final

Analyze, cont.

- Find T_3 from applying equilibrium in the y-direction to the light
- Find T_1 and T_2 from applying equilibrium in the x- and y-directions to the knot

Finalize

- Think about different situations and see if the results are reasonable.

Inclined Planes

Categorize as a particle under a net force since it accelerates.

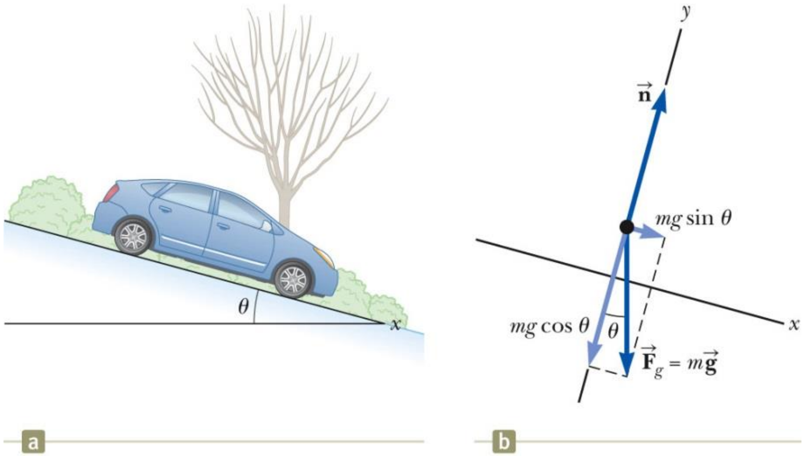
Forces acting on the object:

- The normal force acts perpendicular to the plane.
- The gravitational force acts straight down.

Choose the coordinate system with *x* along the incline and *y* perpendicular to the incline.

Replace the force of gravity with its components.

Apply the model of a particle under a net force to the x-direction and a particle in equilibrium to the y-direction.



Multiple Objects

When two or more objects are connected or in contact, Newton's laws may be applied to the system as a whole and/or to each individual object.

Whichever you use to solve the problem, the other approach can be used as a check.

Multiple Objects, Example – Atwood's Machine

Forces acting on the objects:

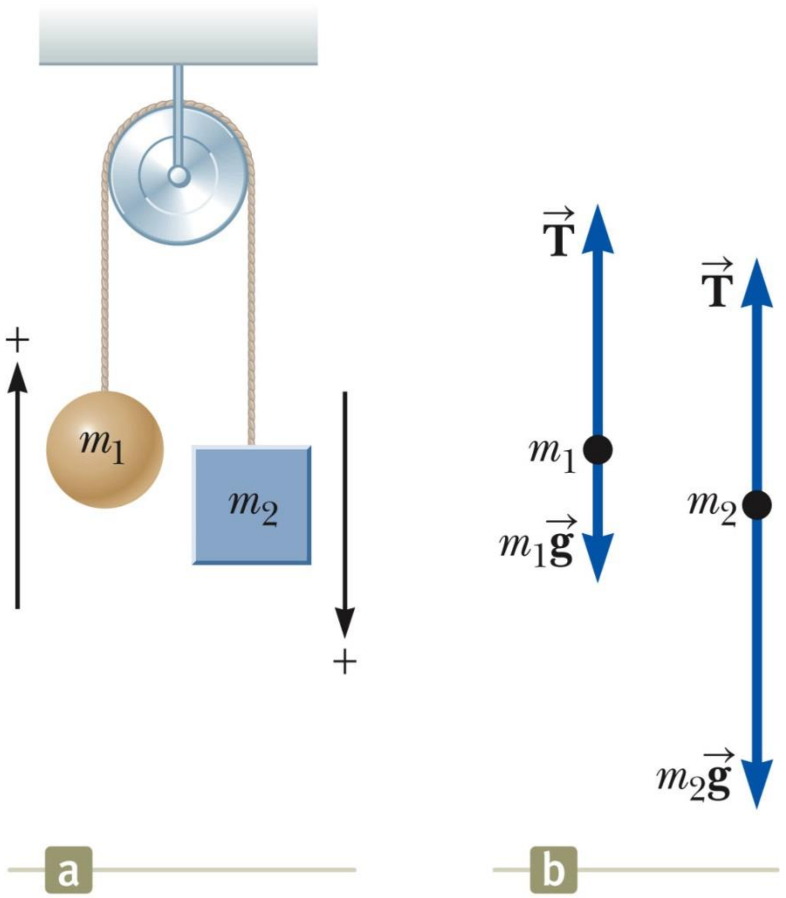
- Tension (same for both objects, one string)
- Gravitational force

Each object has the same acceleration since they are connected.

Draw the free-body diagrams

Apply Newton's Laws

Solve for the unknown(s)



Exploring the Atwood’s Machine

Vary the masses and observe the values of the tension and acceleration.

- Note the acceleration is the same for both objects
- The tension is the same on both sides of the pulley as long as you assume a massless, frictionless pulley.

What if?

- The mass of both objects is the same?
- One of the masses is much larger than the other?

Multiple Objects, Example 2

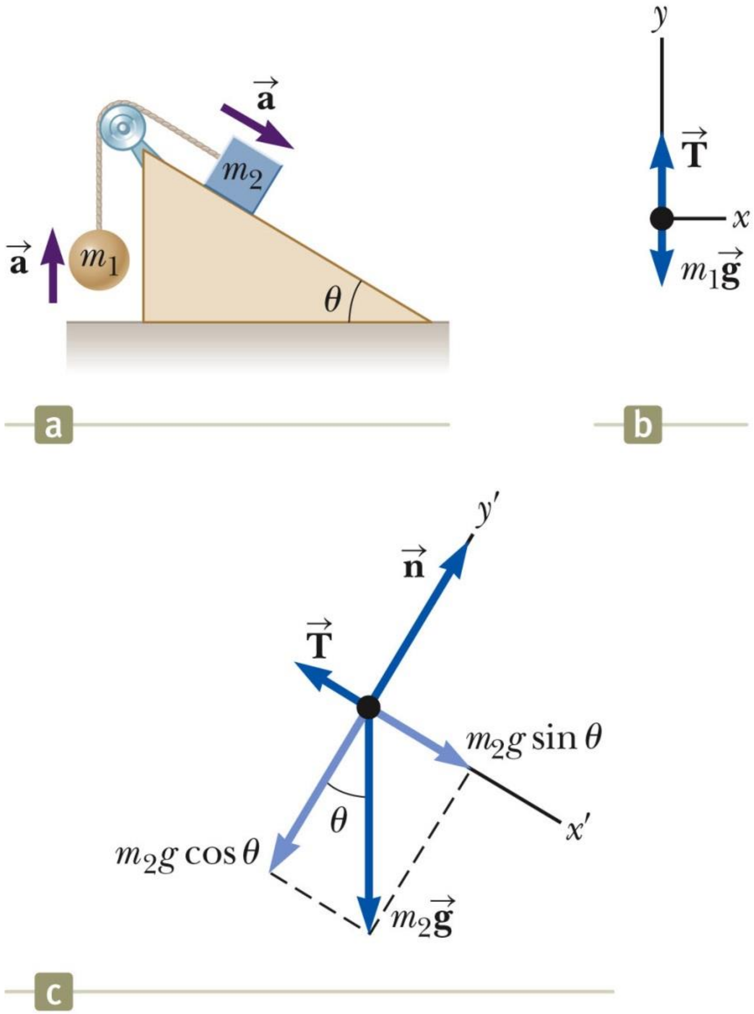
Draw the free-body diagram for each object

- One cord, so tension is the same for both objects
- Connected, so acceleration is the same for both objects

Categorize as particles under a net force

Apply Newton's Laws

Solve for the unknown(s)



Forces of Friction

When an object is in motion on a surface or through a viscous medium, there will be a resistance to the motion.

- This is due to the interactions between the object and its environment.

This resistance is called the *force of friction.*

Forces of Friction, cont.

Friction is proportional to the normal force.

- $f_s \leq \mu_s n$ and $f_k = \mu_k n$
  - μ is the **coefficient of friction**
- These equations relate the magnitudes of the forces; they are not vector equations.
- For static friction, the equals sign is valid only at *impeding* motion, the surfaces are on the verge of slipping.
- Use the inequality for static friction if the surfaces are not on the verge of slipping.

Forces of Friction, final

The coefficient of friction depends on the surfaces in contact.

The force of static friction is generally greater than the force of kinetic friction.

The direction of the frictional force is opposite the direction of motion and parallel to the surfaces in contact.

The coefficients of friction are nearly independent of the area of contact.

Static Friction

Static friction acts to keep the object from moving.

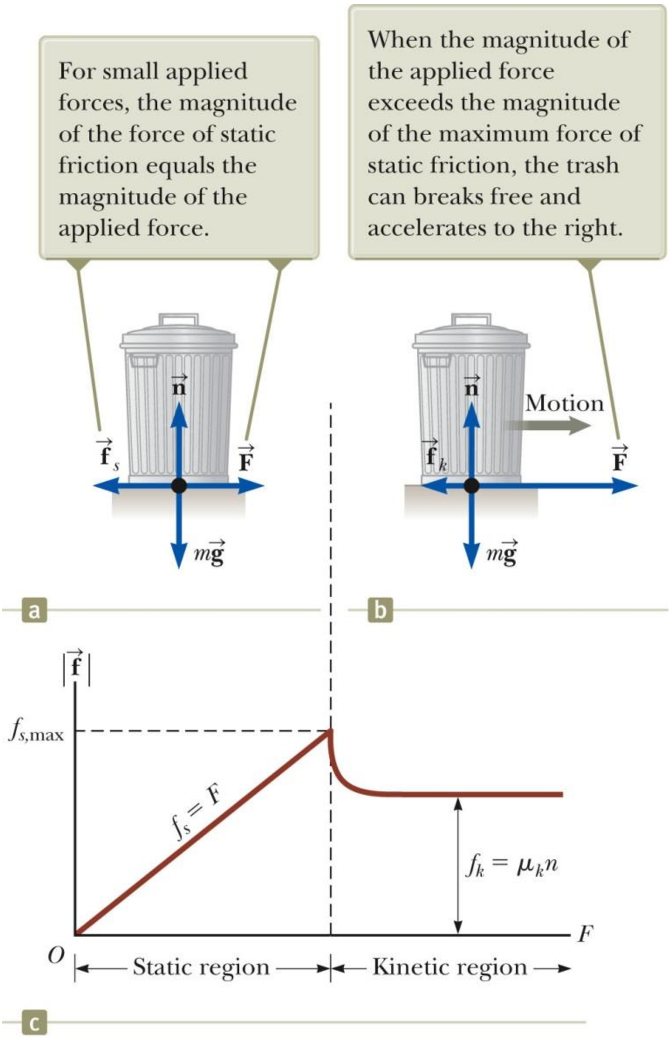
As long as the object is not moving, $f_s = F$

If $\vec{\mathbf{F}}$ increases, so does $\vec{f}_s$

If $\vec{\mathbf{F}}$ decreases, so does $\vec{f}_s$

$f_s \le \mu_s n$

- Remember, the equality holds when the surfaces are on the verge of slipping.

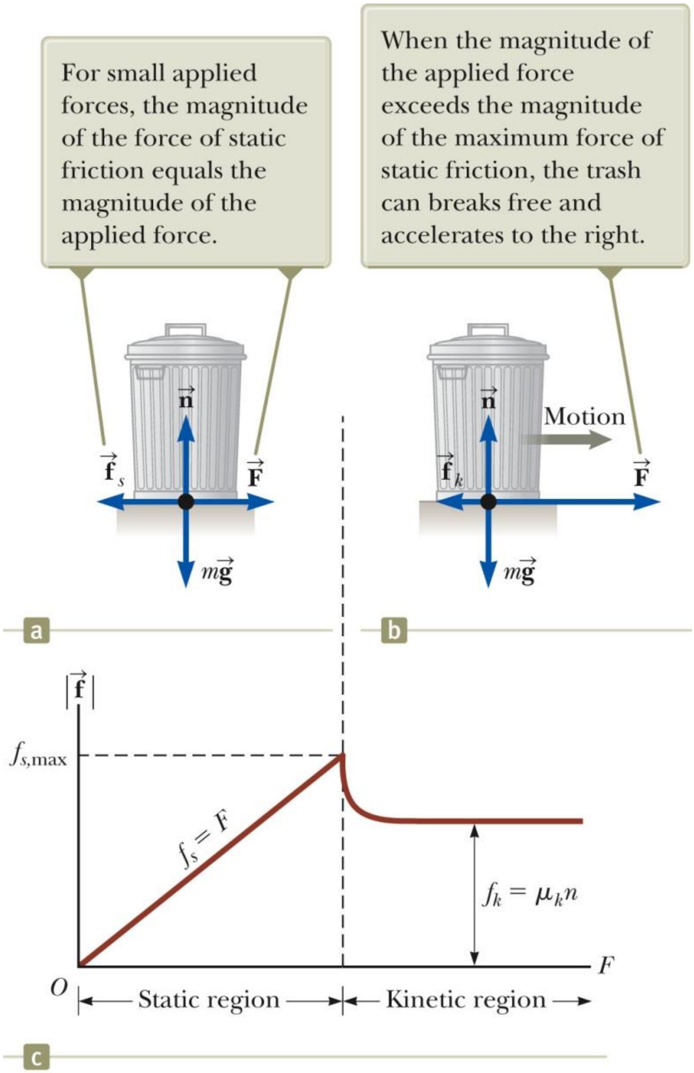


Kinetic Friction

The force of kinetic friction acts when the object is in motion.

Although μ_k can vary with speed, we shall neglect any such variations.

$f_k = \mu_k n$



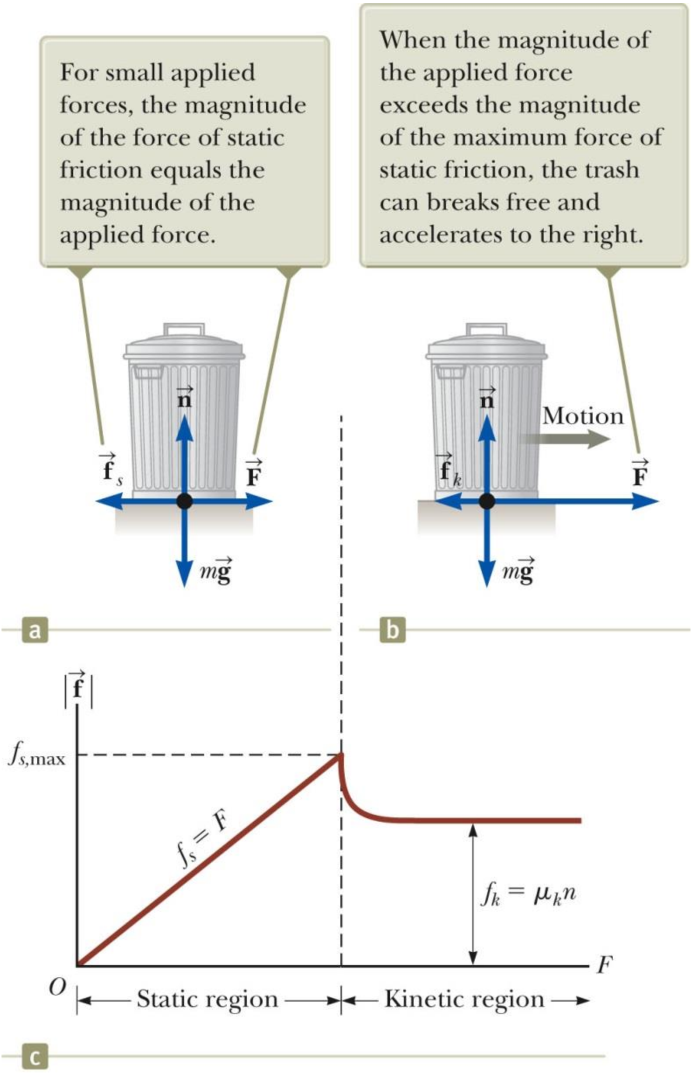
Explore Forces of Friction

Vary the applied force

Note the value of the frictional force

- Compare the values

Note what happens when the can starts to move



Some Coefficients of Friction

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.

Friction in Newton's Laws Problems

Friction is a force, so it simply is included in the $\sum \vec{\mathbf{F}}$ in Newton's Laws.

The rules of friction allow you to determine the direction and magnitude of the force of friction.

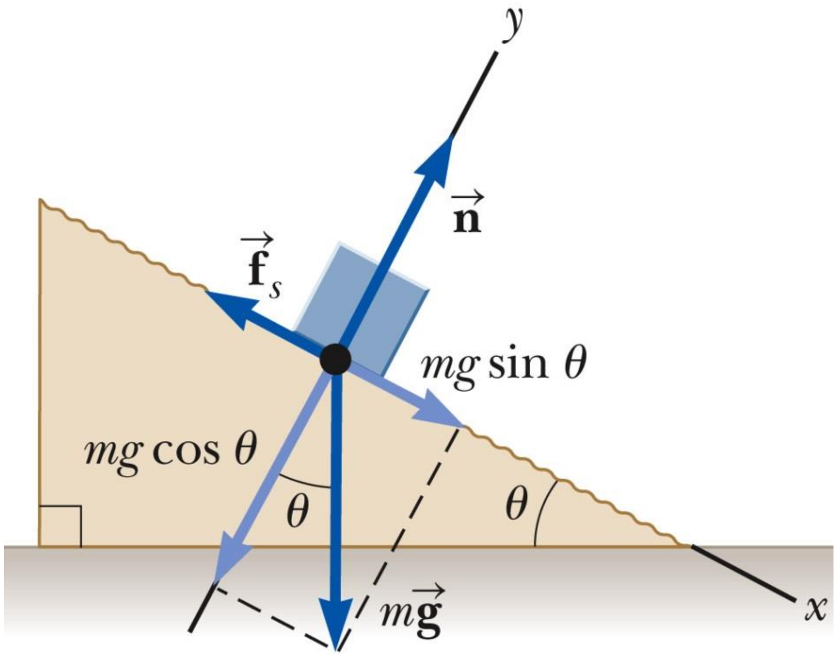
Friction Example, 1

The block is sliding down the plane, so friction acts up the plane.

This setup can be used to experimentally determine the coefficient of friction.

$\mu = \tan\theta$

- For μ_s, use the angle where the block just slips.
- For μ_k, use the angle where the block slides down at a constant speed.



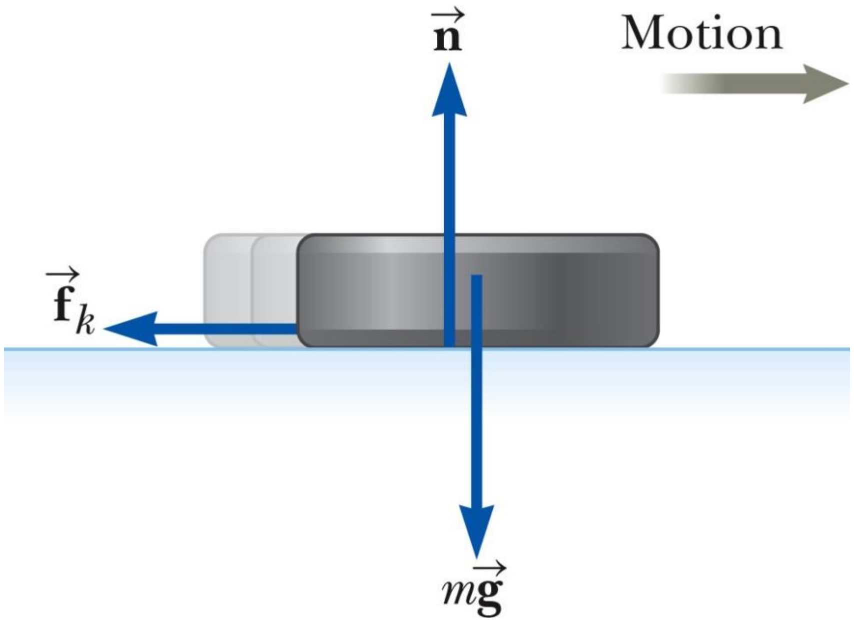
Friction, Example 2

Draw the free-body diagram, including the force of kinetic friction.

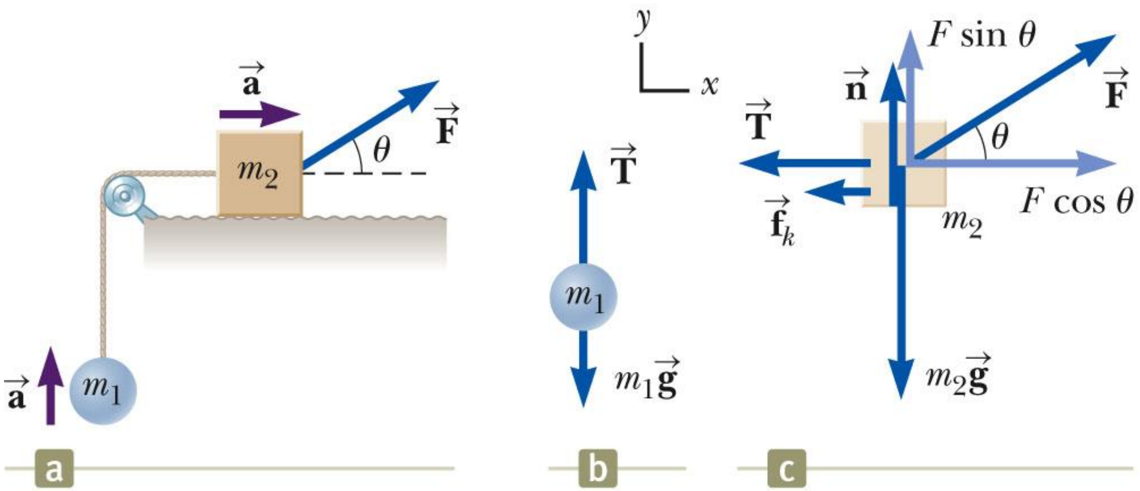
- Opposes the motion
- Is parallel to the surfaces in contact

Continue with the solution as with any Newton's Law problem.

This example gives information about the motion which can be used to find the acceleration to use in Newton's Laws.



Friction, Example 3



Friction acts only on the object in contact with another surface.

Draw the free-body diagrams.

Apply Newton's Laws as in any other multiple object system problem.

Analysis Model Summary

Particle under a net force

- If a particle experiences a non-zero net force, its acceleration is related to the force by Newton's Second Law.
- May also include using a particle under constant acceleration model to relate force and kinematic information.

Particle in equilibrium

- If a particle maintains a constant velocity (including a value of zero), the forces on the particle balance and Newton's Second Law becomes.

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