Chapter 5

The Laws of Motion

Force

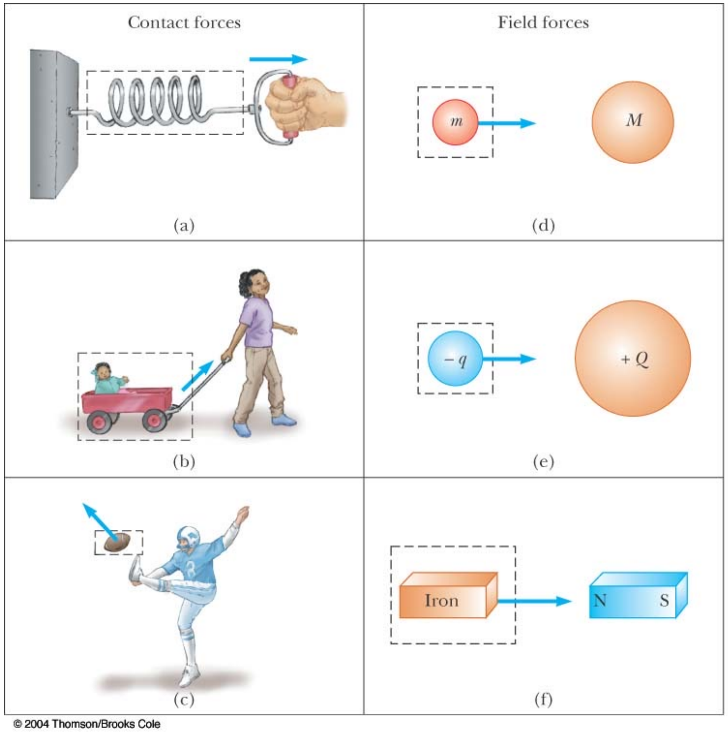
- Forces are what cause any change in the velocity of an object
  - A force is that which causes an acceleration
- The ***net force*** is the vector sum of all the forces acting on an object
  - Also called total force, resultant force, or unbalanced force

Zero Net Force

- When the net force is equal to zero:
  - The acceleration is equal to zero
  - The velocity is constant
- ***Equilibrium*** occurs when the net force is equal to zero
  - The object, if at rest, will remain at rest
  - If the object is moving, it will continue to move at a constant velocity

Classes of Forces

- Contact forces involve physical contact between two objects
- Field forces act through empty space
  - No physical contact is required

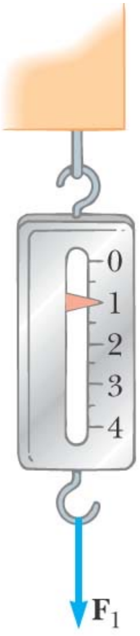


Fundamental Forces

- Gravitational force
  - Between two objects
- Electromagnetic forces
  - Between two charges
- Nuclear force
  - Between subatomic particles
- Weak forces
  - Arise in certain radioactive decay processes

More About Forces

- A spring can be used to calibrate the magnitude of a force
- Forces are vectors, so you must use the rules for vector addition to find the net force acting on an object



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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***

Inertial Frames

- Any reference frame that moves with constant velocity relative to an inertial frame is itself an inertial frame
- A reference frame that moves with constant velocity relative to the distant stars is the best approximation of an inertial frame
  - We can consider the Earth to be such an inertial frame although it has a small centripetal acceleration associated with its motion

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
  - Also tells us that when no force acts on an object, the acceleration of the object is zero

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

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
- 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

Newton's Second Law

- When viewed from an inertial 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 change in motion, as measured by the acceleration
- Algebraically, $\Sigma \mathbf{F} = m\,\mathbf{a}$

More About Newton's Second Law

- $\Sigma \mathbf{F}$ is the net force
  - This is the vector sum of all the forces acting on the object
- Newton's Second Law can be expressed in terms of components:
  - $\Sigma F_x = m\, a_x$
  - $\Sigma F_y = m\, a_y$
  - $\Sigma F_z = m\, a_z$

Units of Force

Table 5.1

Units of Mass, Acceleration, and Force[a]			
System of Units	**Mass**	**Acceleration**	**Force**
SI	kg	m/s^2	$N = kg \cdot m/s^2$
U.S. customary	slug	ft/s^2	$lb = slug \cdot ft/s^2$

[a] 1 N = 0.225 lb.

Gravitational Force

- The gravitational force, $\mathbf{F}_g$, is the force that the earth exerts on an object
- This force is directed toward the center of the earth
- Its magnitude is called the weight of the object
- Weight = $|\mathbf{F}_g| = mg$

More About Weight

- Because it is dependent on *g*, the weight varies with location
  - *g*, and therefore the weight, is less at higher altitudes
- Weight is not an inherent property of the object

Gravitational Mass vs. Inertial Mass

- In Newton's Laws, the mass is the inertial mass and measures the resistance to a change in the object's motion
- In the gravitational force, the mass is determining the gravitational attraction between the object and the Earth
- Experiments show that gravitational mass and inertial mass have the same value

Newton's Third Law

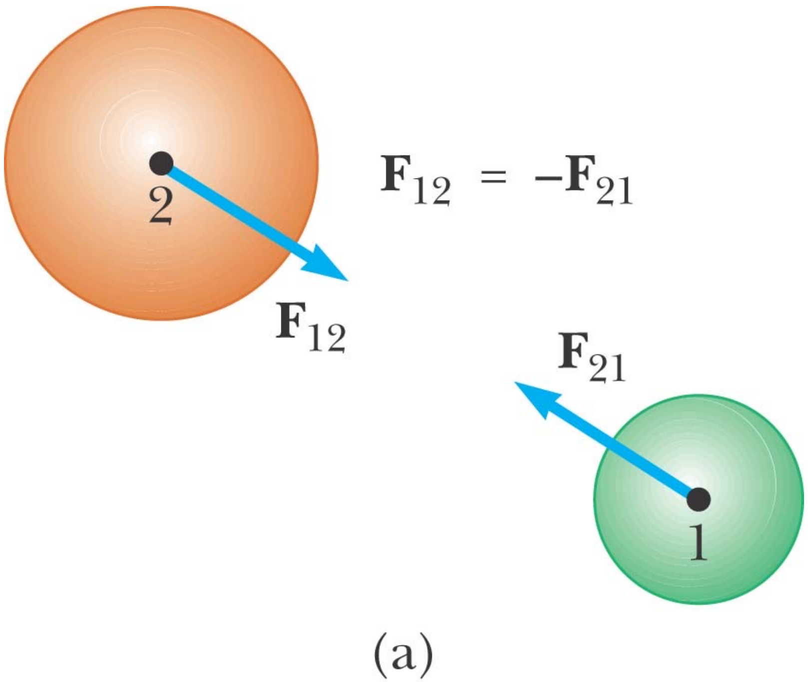
- If two objects interact, the force $\mathbf{F}_{12}$ exerted by object 1 on object 2 is equal in magnitude and opposite in direction to the force $\mathbf{F}_{21}$ exerted by object 2 on object 1
- $\mathbf{F}_{12} = - \mathbf{F}_{21}$
  - Note on notation: $\mathbf{F}_{AB}$ is the force exerted by A on B

Newton’s Third Law, Alternative Statements

- Forces always occur in pairs
- A single isolated force cannot exist
- 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

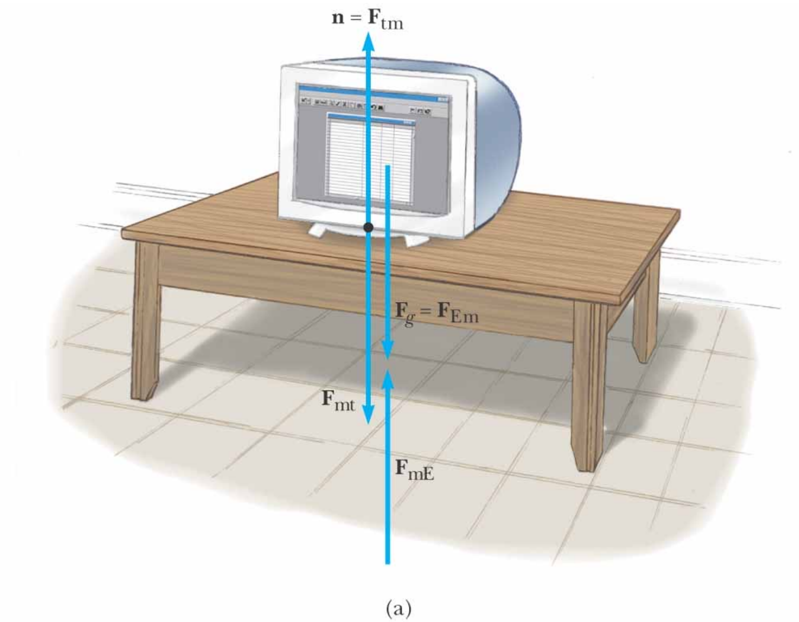
Action-Reaction Examples, 1

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



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 (**F**$_g$, Earth on monitor) force is equal in magnitude and opposite in direction to the reaction force, the force the monitor exerts on the Earth



Free Body Diagram

- In a free body diagram, you want the forces acting on a particular object
- The normal force and the force of gravity are the forces that act on the monitor

(b)

Applications of Newton’s Law

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

Objects 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**
- Mathematically, the net force acting on the object is zero

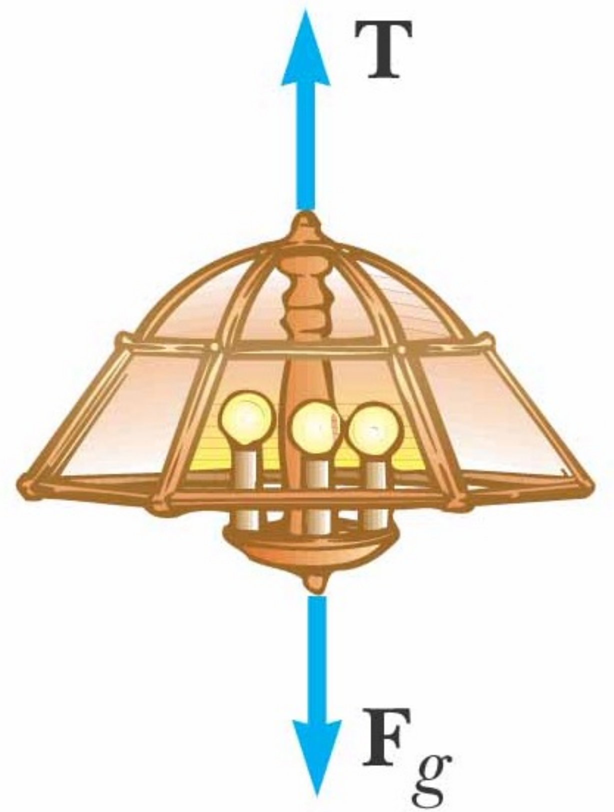
$$\sum F = 0$$

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

Equilibrium, Example 1a

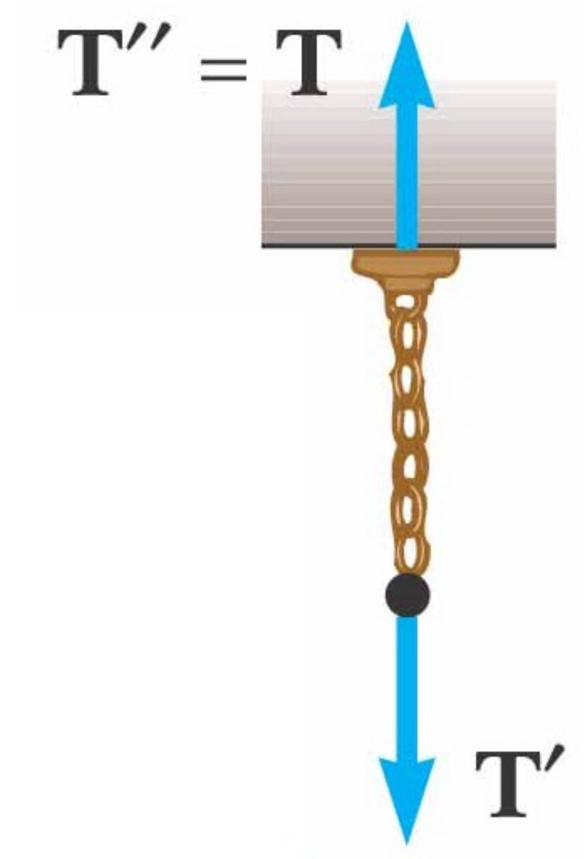
- A lamp is suspended from a chain of negligible mass
- The forces acting on the lamp are
  - the force of gravity ($\mathbf{F}_g$)
  - the tension in the chain (**T**)
- Equilibrium gives

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



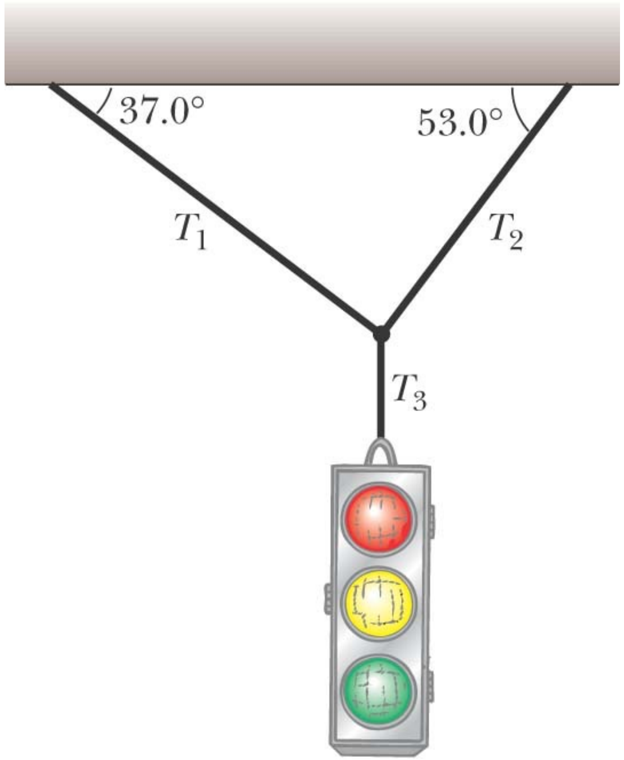
Equilibrium, Example 1b

- The forces acting on the chain are **T**′ and **T**″
- **T**″ is the force exerted by the ceiling
- **T**′ is the force exerted by the lamp
- **T**′ is the reaction force to **T**
- Only **T** is in the free body diagram of the lamp, since **T**′ and **T**″ do not act on the lamp



Equilibrium, Example 2a

- Example 5.4
- Conceptualize the traffic light
- Categorize as an equilibrium problem
  - No movement, so acceleration is zero



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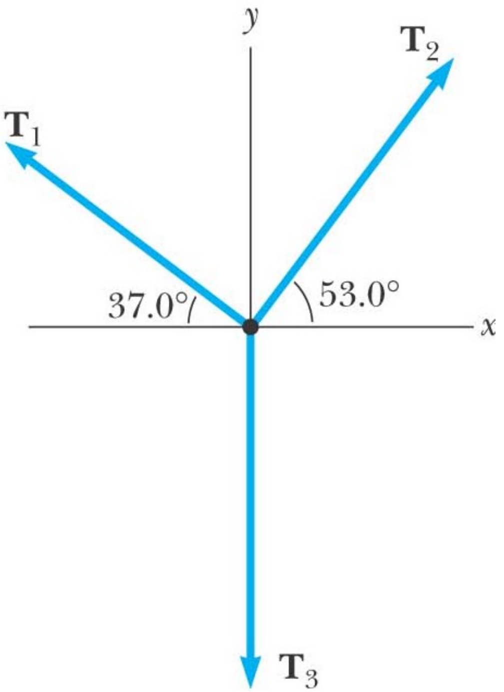
Equilibrium, Example 2b

- Analyze
  - Need two free-body diagrams
  - Apply equilibrium equation to the light and find $\mathbf{T}_3$
  - Apply equilibrium equations to the knot and find $\mathbf{T}_1$ and $\mathbf{T}_2$

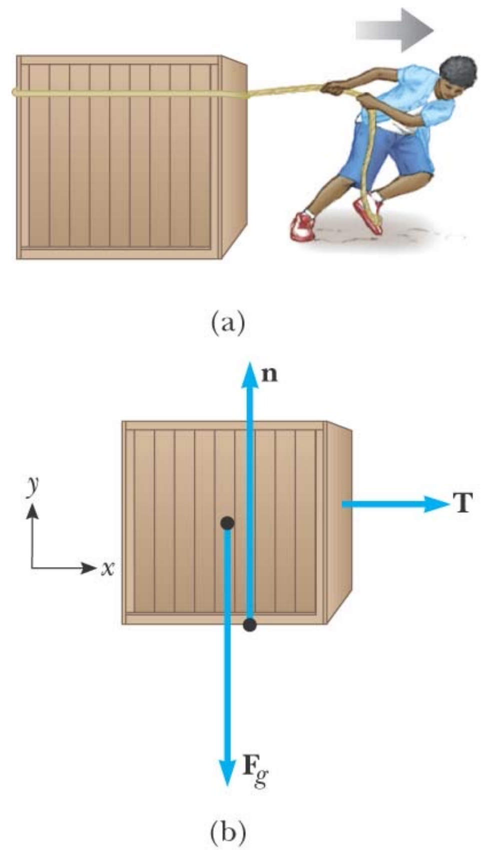


Objects Experiencing a Net Force

- If an object that can be modeled as a particle experiences an acceleration, there must be a nonzero net force acting on it.
- Draw a free-body diagram
- Apply Newton's Second Law in component form

Newton's Second Law, Example 1a

- Forces acting on the crate:
  - A tension, the magnitude of force **T**
  - The gravitational force, $\mathbf{F}_g$
  - The normal force, **n**, exerted by the floor



Newton's Second Law, Example 1b

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

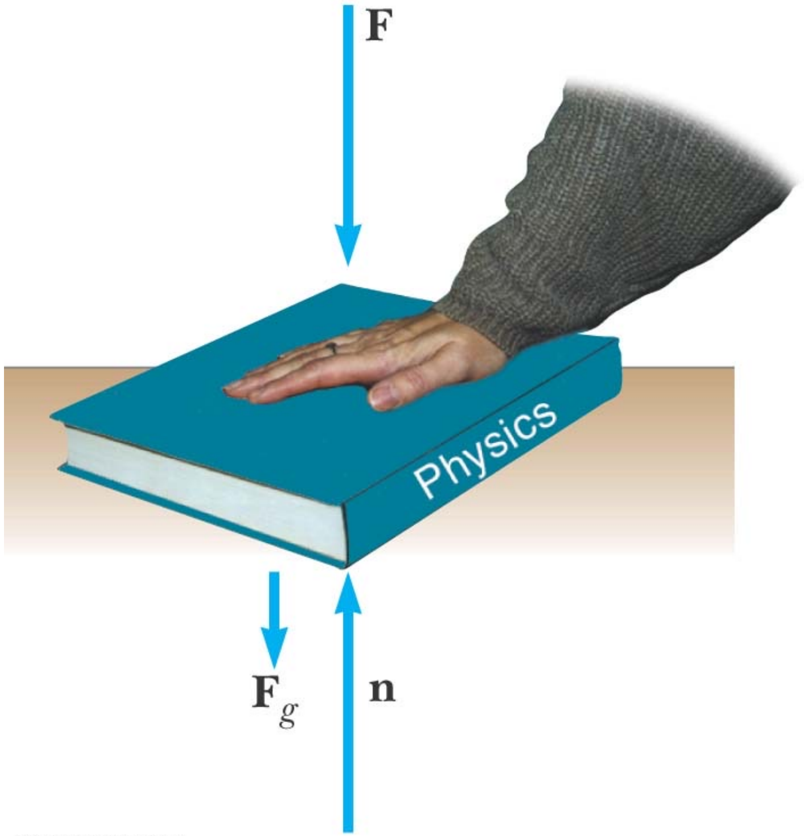
Note About the Normal Force

- The normal force is **not** always equal to the gravitational force of the object
- For example, in this case

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

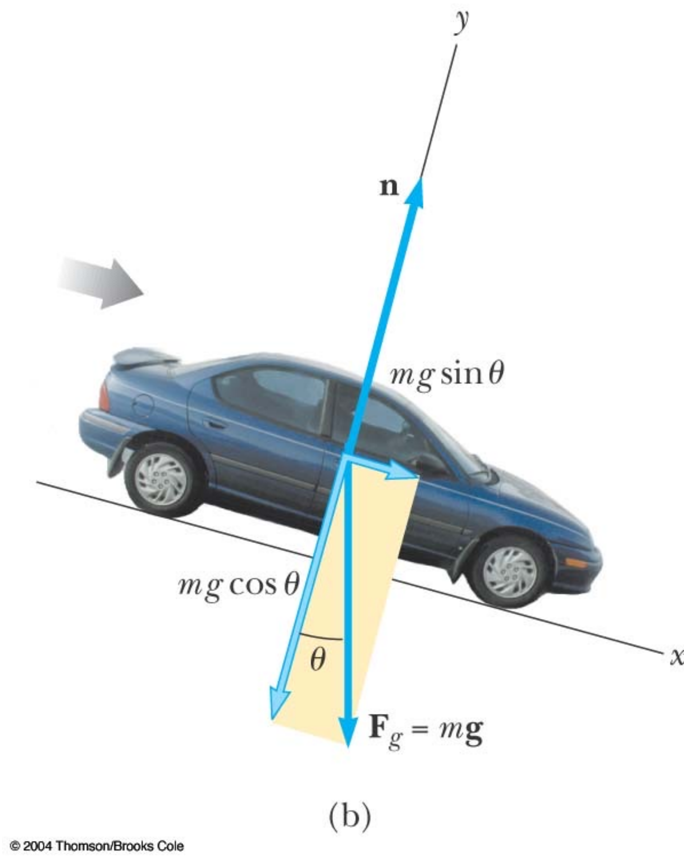
$$\text{and } n = F_g + F$$

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



Inclined Planes

- Forces acting on the object:
  - The normal force, **n**, acts perpendicular to the plane
  - The gravitational force, $\mathbf{F}_g$, 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



Multiple Objects

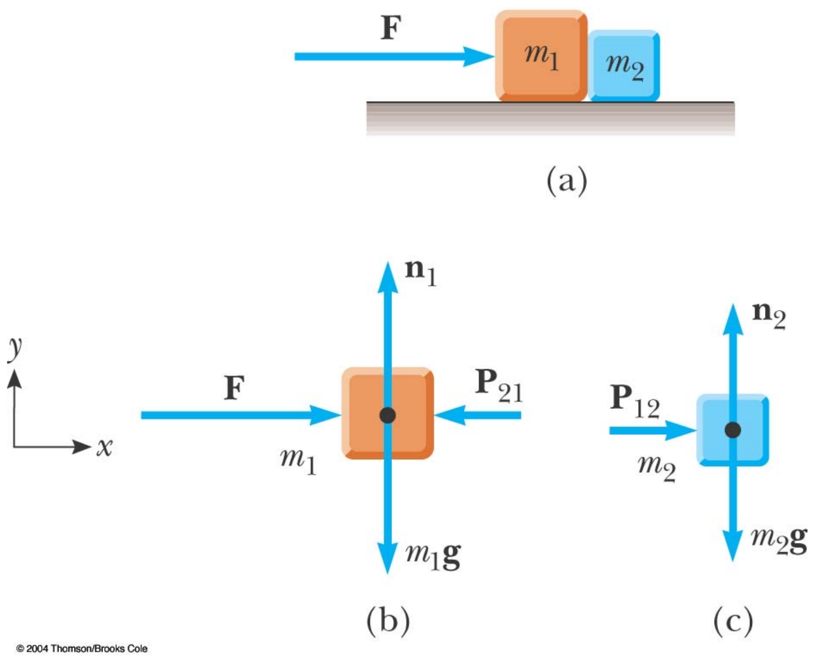
- When two or more objects are connected or in contact, Newton's laws may be applied to the system as a whole and/or to each individual object
- Whichever you use to solve the problem, the other approach can be used as a check

Multiple Objects, Example 1

- First treat the system as a whole:

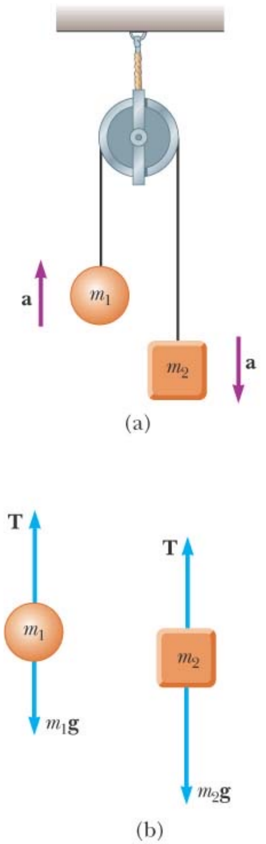
$$\sum F_x = m_{\text{system}} a_x$$

- Apply Newton's Laws to the individual blocks
- Solve for unknown(s)
- Check: $|\mathbf{P}_{21}| = |\mathbf{P}_{12}|$

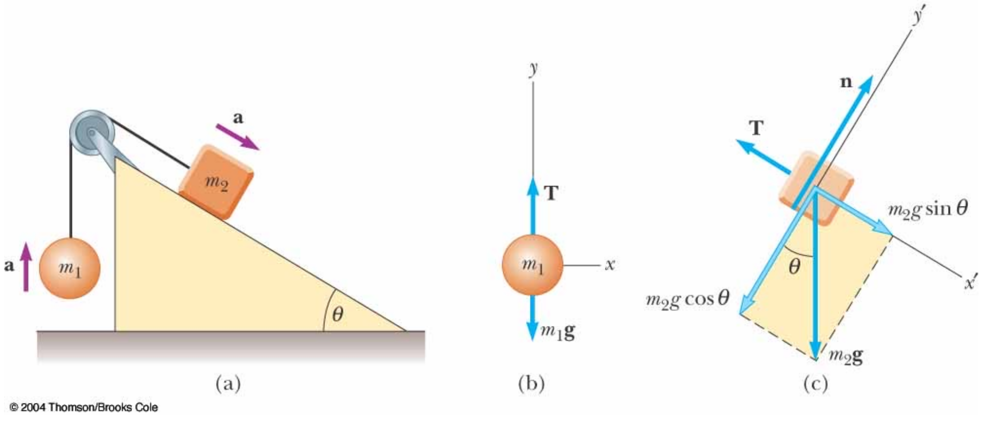


Multiple Objects, Example 2

- 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)



Multiple Objects, Example 3



- 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
- Apply Newton’s Laws
- Solve for the unknown(s)

Problem-Solving Hints Newton's Laws

- Conceptualize the problem – draw a diagram
- Categorize the problem
  - Equilibrium ($\Sigma\mathbf{F} = 0$) or Newton's Second Law ($\Sigma\mathbf{F} = m\,\mathbf{a}$)
- Analyze
  - Draw free-body diagrams for each object
  - Include only forces acting on the object

Problem-Solving Hints Newton's Laws, cont

- Analyze, cont.
  - Establish coordinate system
  - 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

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.

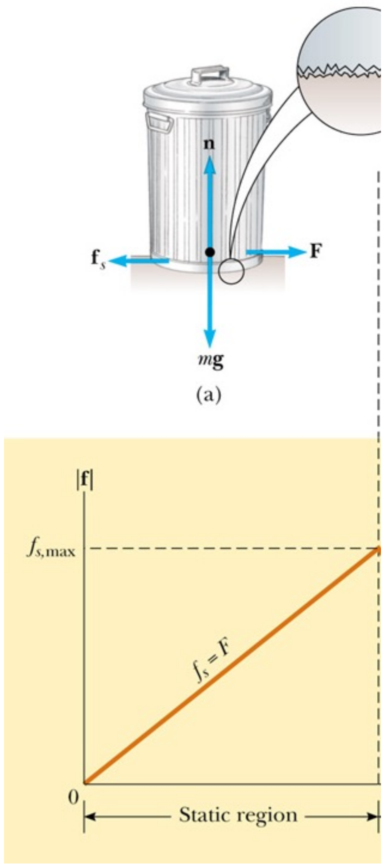
- Friction is proportional to the normal force
  - $f_s \leq \mu_s n$ and $f_k = \mu_k n$
  - These equations relate the magnitudes of the forces, they are not vector equations
- The force of static friction is generally greater than the force of kinetic friction
- The coefficient of friction (μ) depends on the surfaces in contact

Forces of Friction, final

- 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

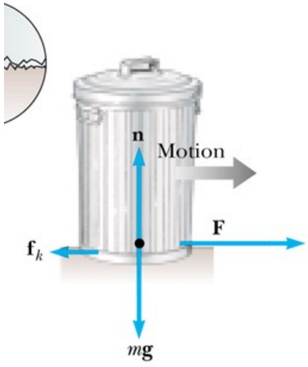
Static Friction

- Static friction acts to keep the object from moving
- If **F** increases, so does $\boldsymbol{f}_s$
- If **F** decreases, so does $\boldsymbol{f}_s$
- $f_s \le \mu_s n$ where the equality holds when the surfaces are on the verge of slipping
  - Called impending motion



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
- $f_k = \mu_k n$



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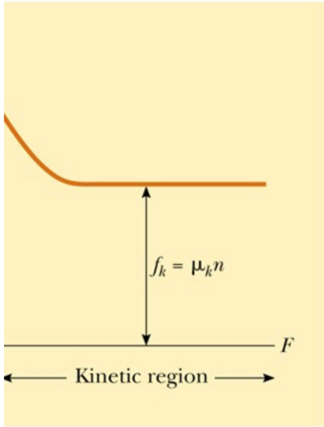


Some Coefficients of Friction

Table 5.2

Coefficients of Friction[a]

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

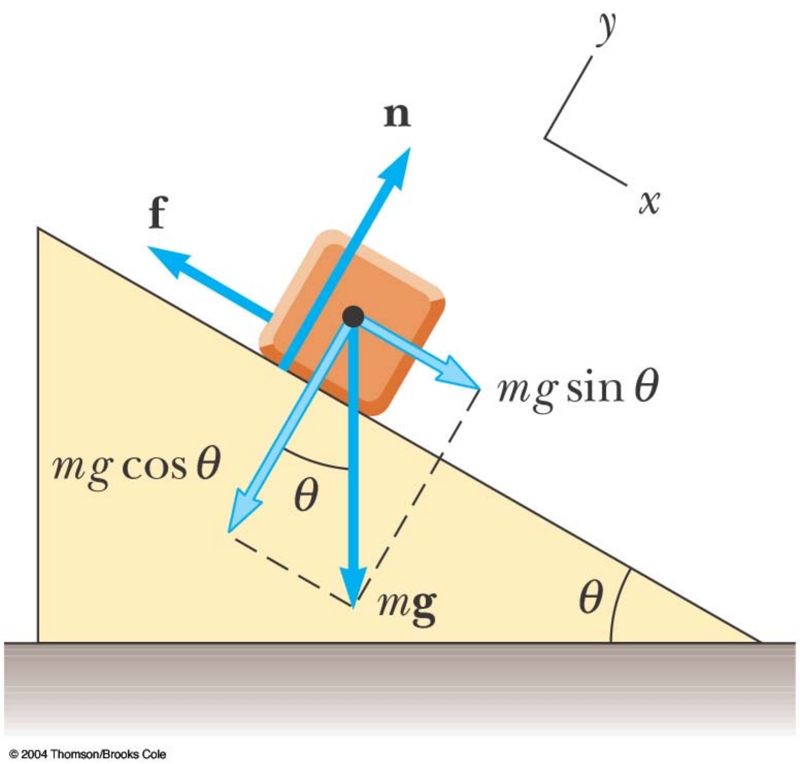
[a] All values are approximate. In some cases, the coefficient of friction can exceed 1.0.

Friction in Newton's Laws Problems

- Friction is a force, so it simply is included in the $\Sigma\mathbf{F}$ in Newton's Laws
- The rules of friction allow you to determine the direction and magnitude of the force of friction

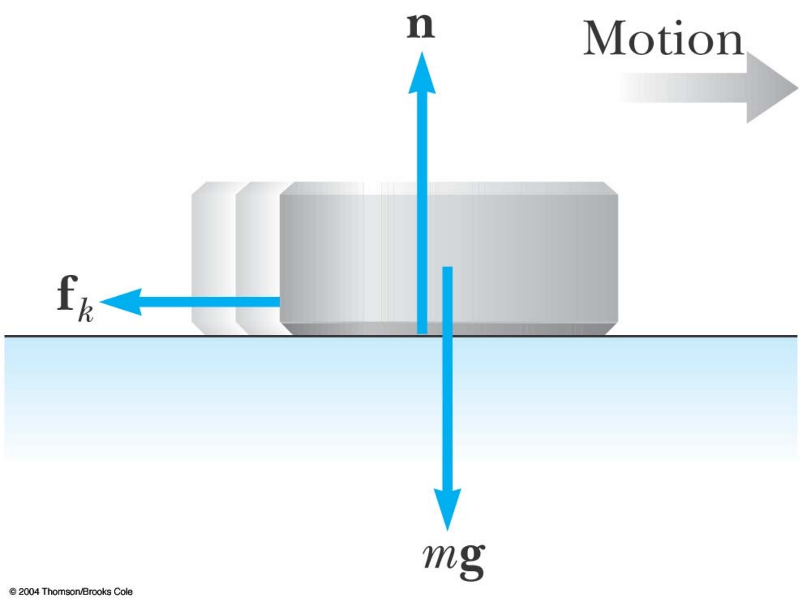
Friction Example, 1

- 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

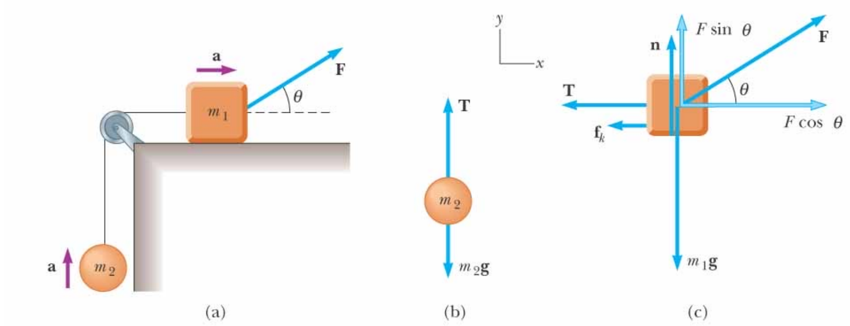


Friction, Example 2

- 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



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