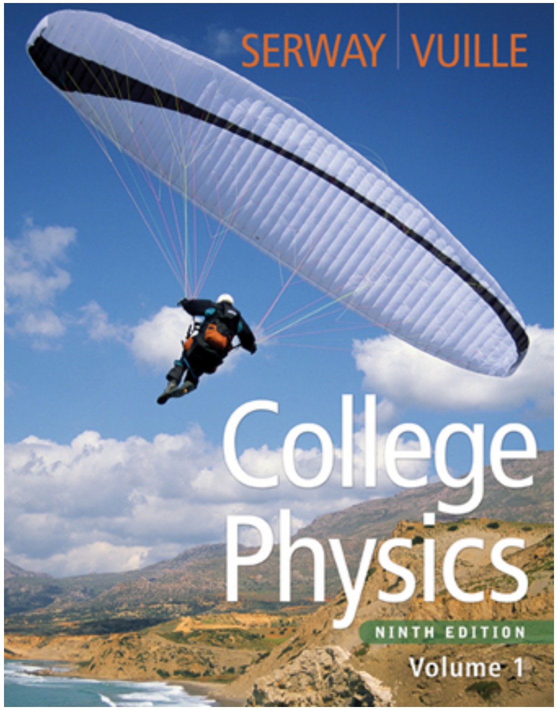

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Raymond A. Serway
Chris Vuille

Chapter Four

The Laws of Motion

Classical Mechanics

- Describes the relationship between the motion of objects in our everyday world and the forces acting on them
- Conditions when Classical Mechanics does not apply
  - Very tiny objects (< atomic sizes)
  - Objects moving near the speed of light

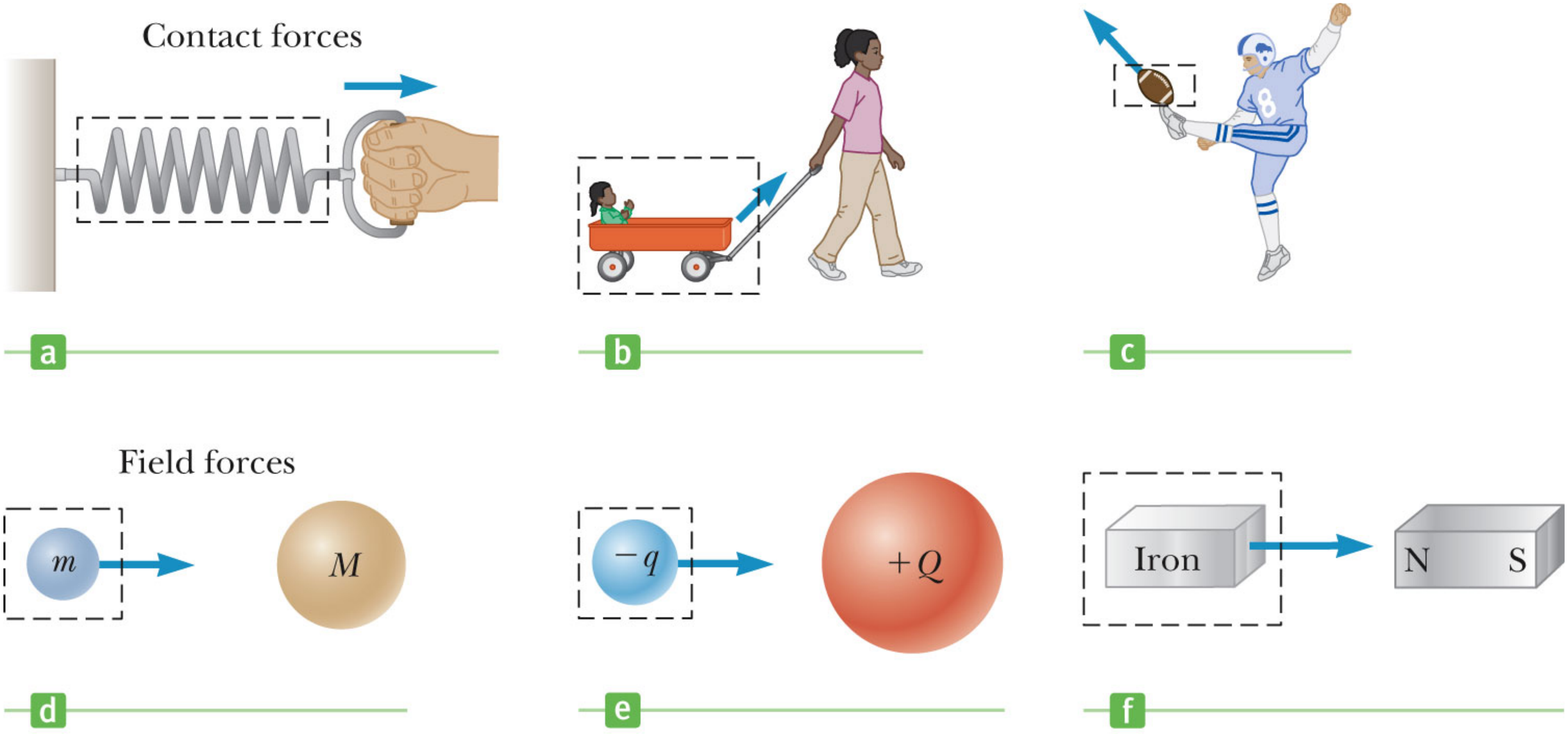
Newton's Laws

- This chapter will look at an introduction to Newton's three laws of motion and his law of gravity
- These laws are considered among the greatest achievements of the human mind

Forces

- Commonly imagined as a push or pull on some object
- Vector quantity
- May be a **contact force** or a **field force**
  - Contact forces result from physical contact between two objects
  - Field forces act between disconnected objects

Contact and Field Forces

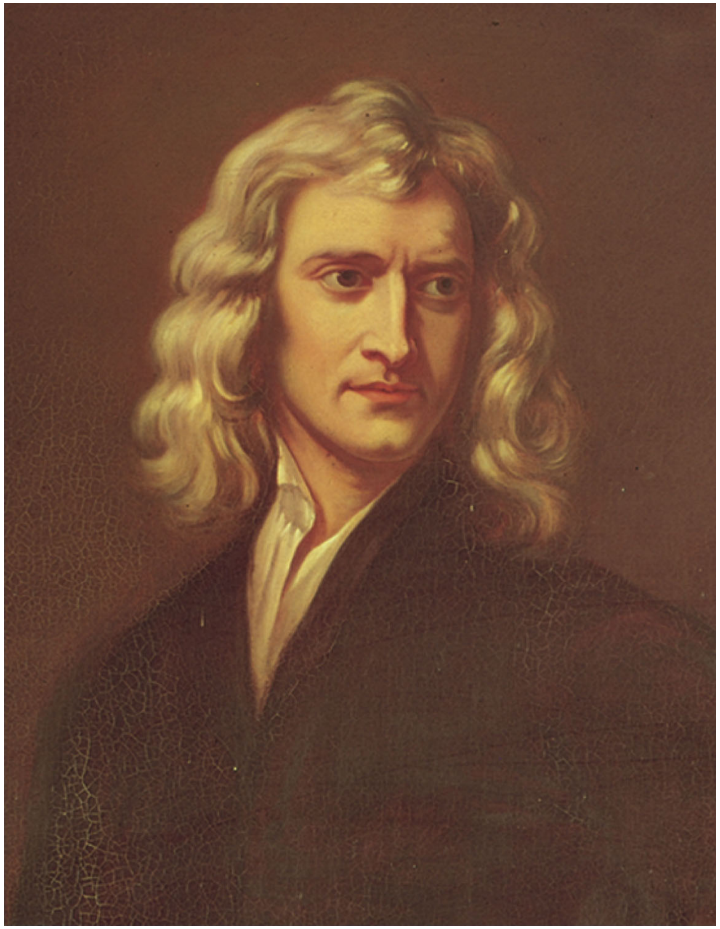


Fundamental Forces

- Types
  - Strong nuclear force
  - Electromagnetic force
  - Weak nuclear force
  - Gravity
- Characteristics
  - All field forces
  - Listed in order of decreasing strength
  - Only gravity and electromagnetic in mechanics

Sir Isaac Newton

- 1642 – 1727
- Formulated basic concepts and laws of mechanics
- Universal Gravitation
- Calculus
- Light and optics



Newton's First Law

- An object moves with a velocity that is constant in magnitude and direction, unless acted on by a nonzero net force
  - The net force is defined as the vector sum of all the external forces exerted on the object

External and Internal Forces

- External force
  - Any force that results from the interaction between the object and its environment
- Internal forces
  - Forces that originate within the object itself
  - They cannot change the object's velocity

Inertia

- Is the tendency of an object to continue in its original motion
  - In the absence of a force
- Thought experiment
  - Hit a golf ball
  - Hit a bowling ball with the same force
  - The golf ball will travel farther
  - Both resist changes in their motion

Mass

- A measure of the resistance of an object to changes in its motion due to a force
  - The larger the mass, the less it accelerates under the action of a given force
- SI units are kg
- Scalar quantity

Newton's Second Law

- The acceleration of an object is directly proportional to the net force acting on it and inversely proportional to its mass.

$$\vec{\mathbf{a}} = \frac{\sum \vec{\mathbf{F}}}{m} \text{ or } \sum \vec{\mathbf{F}} = m\vec{\mathbf{a}}$$

- Can also be applied three-dimensionally

Units of Force

- SI unit of force is a Newton (N)

$$1\,\text{N} \equiv 1\,\frac{\text{kg m}}{\text{s}^2}$$

- US Customary unit of force is a pound (lb)
  - 1 N = 0.225 lb
- See table 4.1 for a summary of units

Some Notes About Forces

- Forces cause *changes* in motion
  - Motion can occur in the absence of forces
- All the forces acting on an object are added as vectors to find the net force acting on the object
  - $m\vec{\mathbf{a}}$ is *not* a force itself
- Newton's Second Law is a vector equation

Gravitational Force

- Mutual force of attraction between any two objects
- Expressed by Newton's Law of Universal Gravitation:
  - Every particle in the Universe attracts every other particle with a force that is directly proportional to the product of the masses of the particles and inversely proportional to the square of the distance between them

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

Weight

- The magnitude of the gravitational force acting on an object of mass *m* near the Earth's surface is called the weight *w* of the object
  - $w = m\,g$ is a special case of Newton's Second Law
    - *g* is the acceleration due to gravity
- *g* can also be found from the Law of Universal Gravitation

More about weight

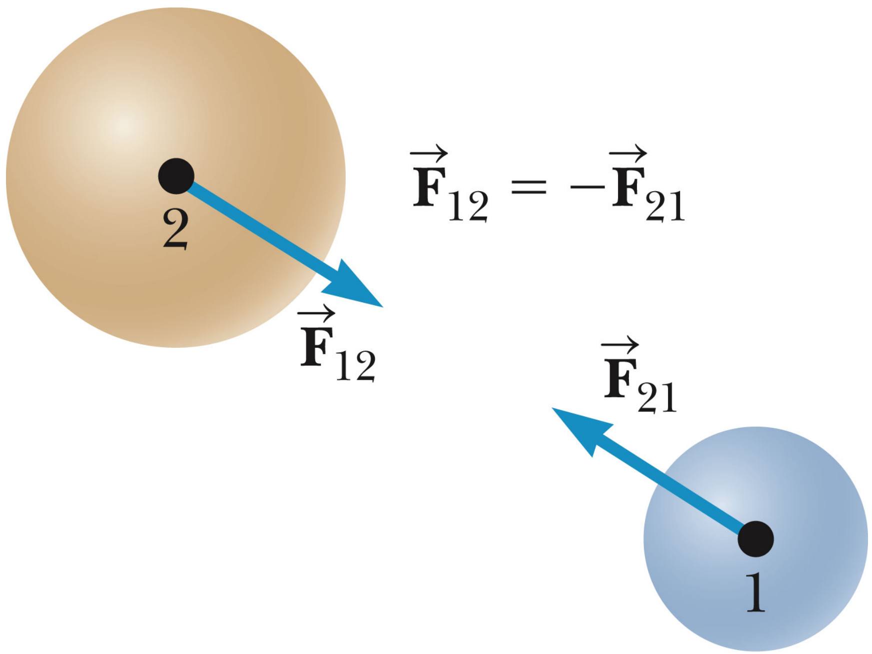
- Weight is **not** an inherent property of an object
  - Mass **is** an inherent property
- Weight depends upon location

Newton’s Third Law

- If object 1 and object 2 interact, the force exerted by object 1 on object 2 is equal in magnitude but opposite in direction to the force exerted by object 2 on object 1.
  - $\vec{\mathbf{F}}_{12} = -\vec{\mathbf{F}}_{21}$
  - Equivalent to saying a single isolated force cannot exist

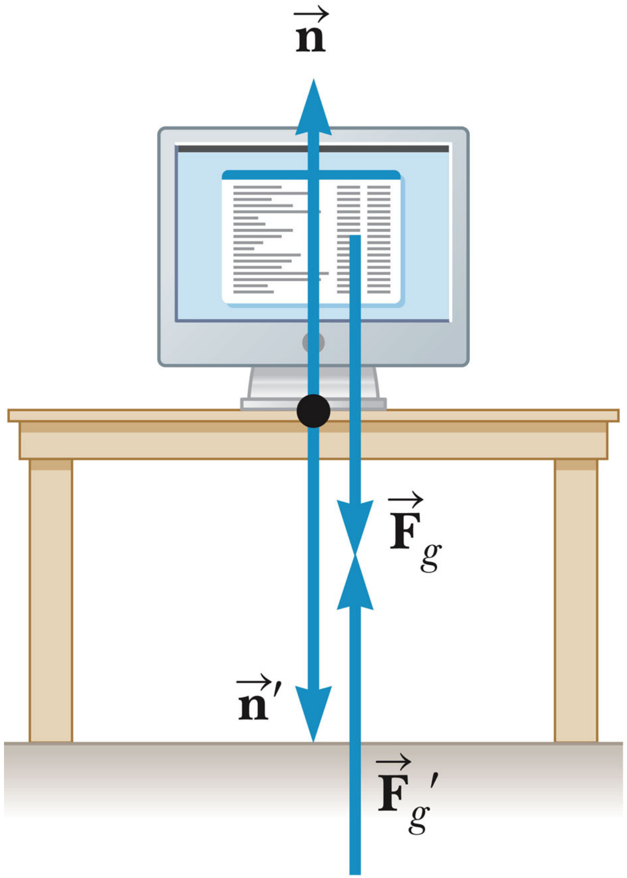
Newton's Third Law cont.

- F_{12} may be called the *action* force and F_{21} the *reaction* force
  - Actually, either force can be the action or the reaction force
- The action and reaction forces act on **different** objects



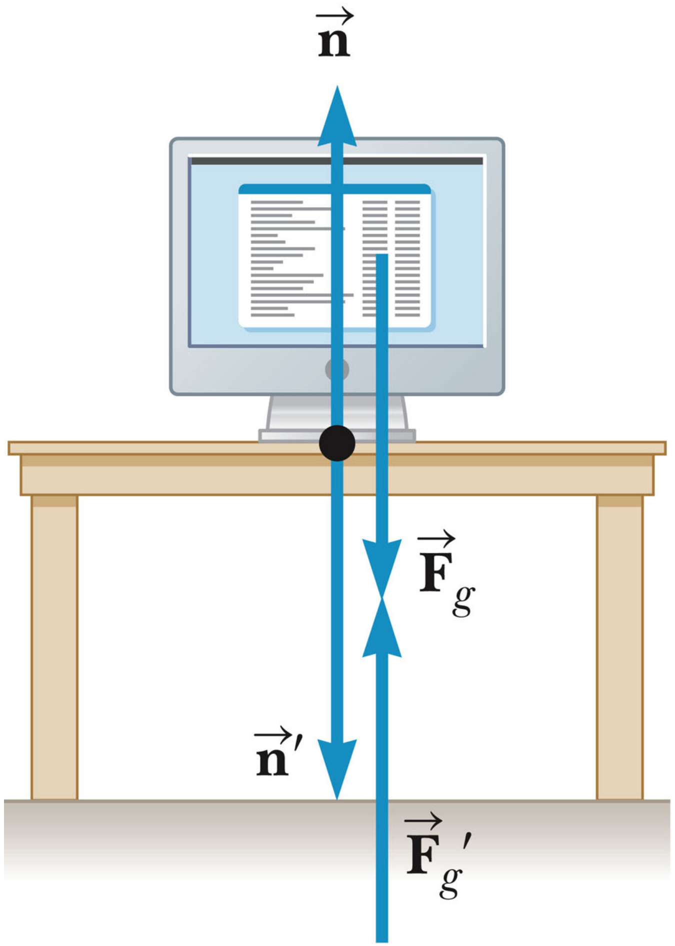
Some Action-Reaction Pairs

- $\vec{\mathbf{n}}$ *and* $\vec{\mathbf{n}}'$
  - $\vec{\mathbf{n}}$ is the *normal* force, the force the table exerts on the TV
  - $\vec{\mathbf{n}}$ is always perpendicular to the surface
  - $\vec{\mathbf{n}}'$ is the reaction – the TV on the table
  - $\vec{\mathbf{n}} = -\vec{\mathbf{n}}'$



More Action-Reaction pairs

- $\vec{\mathbf{F}}_g$ *and* $\vec{\mathbf{F}}_g'$
  - $\vec{\mathbf{F}}_g$ is the force the Earth exerts on the object
  - $\vec{\mathbf{F}}_g'$ is the force the object exerts on the earth
  - $\vec{\mathbf{F}}_g = -\vec{\mathbf{F}}_g'$



Forces Acting on an Object

- Newton's Law uses the forces acting *on* an object
- $\vec{\mathbf{n}}$ and $\vec{\mathbf{F}}_g$ are acting on the object
- $\vec{\mathbf{n}}'$ and $\vec{\mathbf{F}}_g'$ are acting on other objects

Applications of Newton's Laws

- Assumptions
  - Objects behave as particles
    - Can ignore rotational motion (for now)
  - Masses of strings or ropes are negligible
  - Interested only in the forces acting on the object
    - Can neglect reaction forces

More Assumptions – Ropes

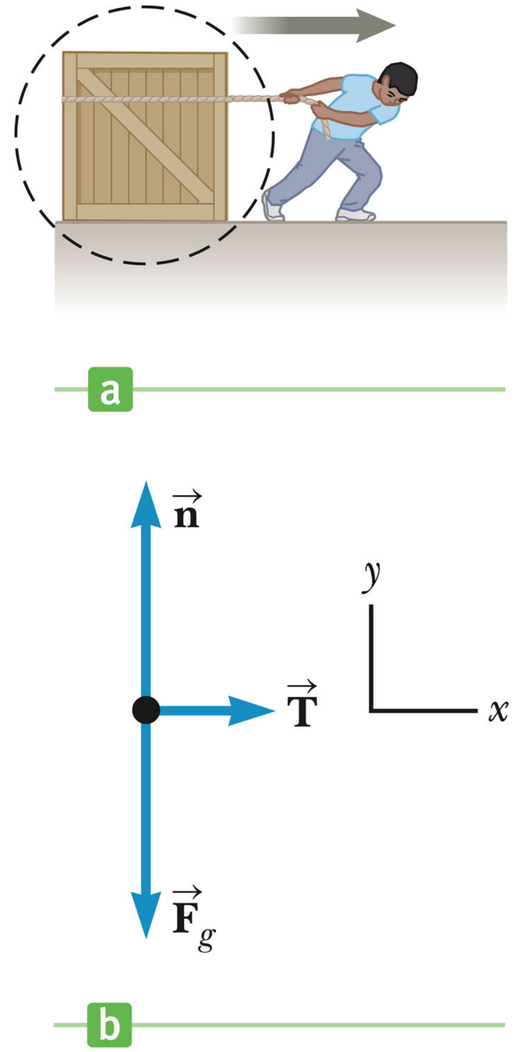
- Ignore any frictional effects of the rope
- Ignore the mass of the rope
- The magnitude of the force exerted along the rope is called the **tension**
- The tension is the same at all points in the rope

Free Body Diagram

- A diagram of the forces acting on an object
- Must identify all the forces acting on the object of interest
- Choose an appropriate coordinate system
- If the free body diagram is incorrect, the solution will likely be incorrect

Free Body Diagram, Example

- The magnitude of force **T** is the tension acting on the box
  - The tension is the same at all points along the rope
- $\vec{\mathbf{n}}$ and $\vec{\mathbf{F}}_g$ are the forces exerted by the earth and the ground



Free Body Diagram, final

- Only forces acting directly on the object are included in the free body diagram
  - Reaction forces act on other objects and so are not included
  - The reaction forces do not directly influence the object's motion

Solving Newton's Second Law Problems

- **Read** the problem at least once
- **Draw** a picture of the system
  - Identify the object of primary interest
  - Indicate forces with arrows
- **Label** each force
  - Use labels that bring to mind the physical quantity involved

Solving Newton's Second Law Problems, cont

- **Draw** a free body diagram
  - If additional objects are involved, draw separate free body diagrams for each object
  - Choose a convenient coordinate system for each object
- **Apply Newton's Second Law**
  - The x- and y-components should be taken from the vector equation and written separately
- **Solve** for the unknown(s)

Equilibrium

- An object either at rest or moving with a constant velocity is said to be in *equilibrium*
- The net force acting on the object is zero (since the acceleration is zero)

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

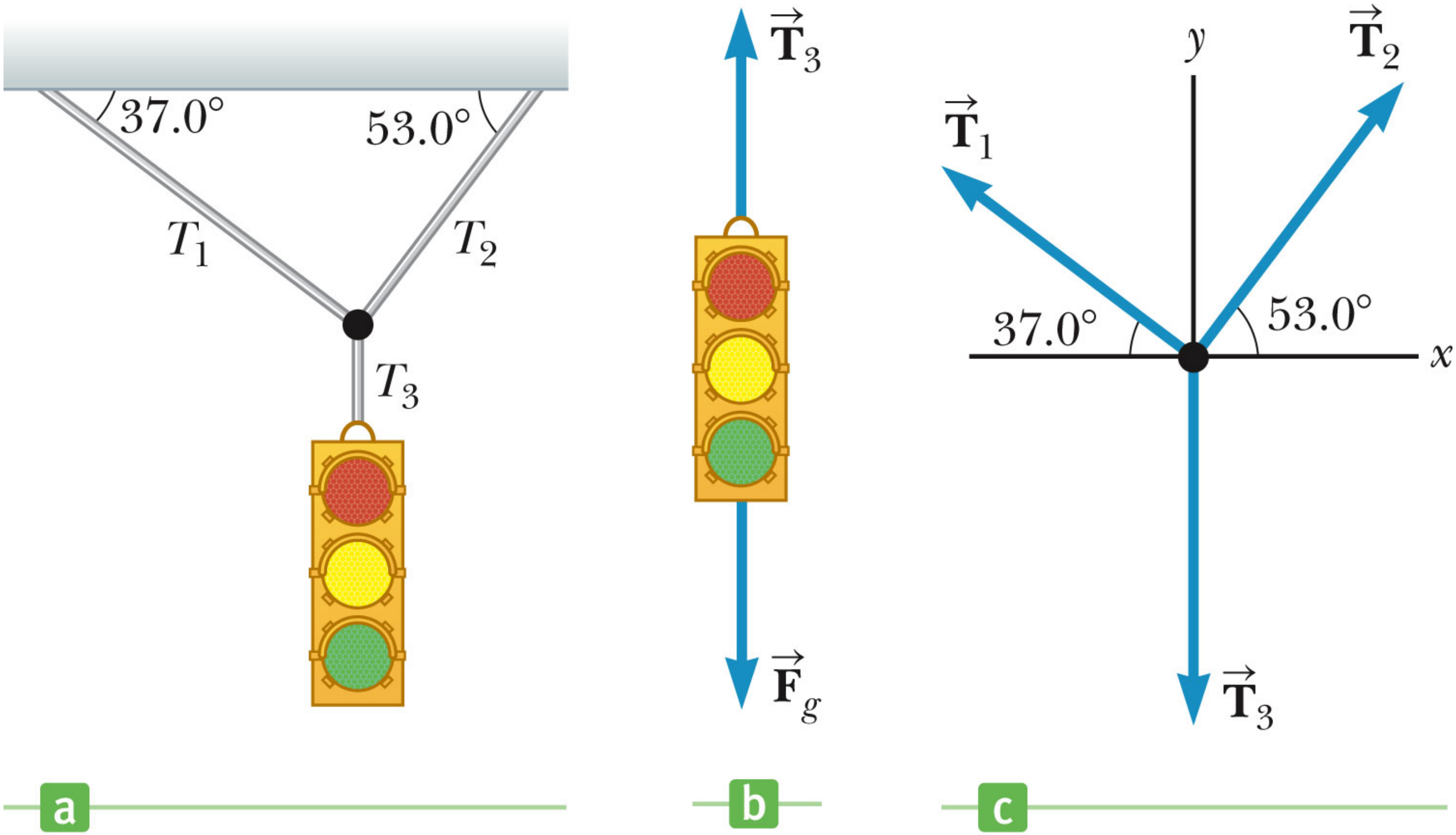
Equilibrium cont.

- Easier to work with the equation in terms of its components:

$$\sum F_x = 0 \; and \; \sum F_y = 0$$

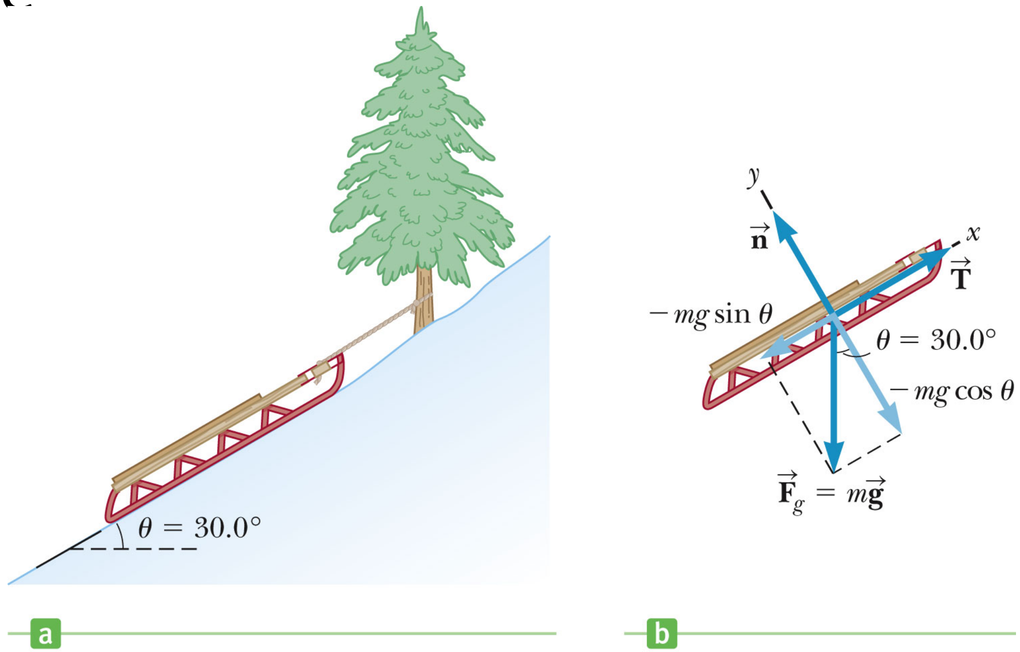
- This could be extended to three dimensions
- A zero net force does *not* mean the object is not moving, but that it is not accelerating

Equilibrium Example – Free Body Diagrams



Inclined Planes

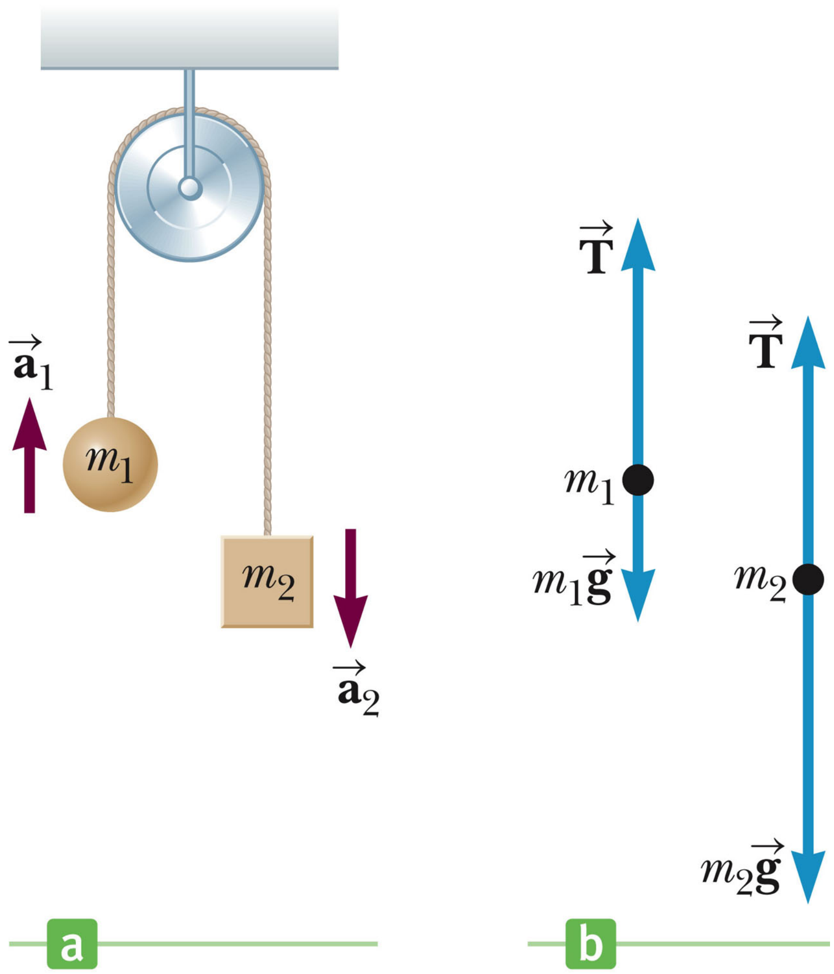
- Choose the coordinate system with x along the incline and y perpendicular to the incline
- Replace the force of gravity with its components



Multiple Objects – Example

- When you have more than one object, the problem-solving strategy is applied to each object
- Draw free body diagrams for each object
- Apply Newton's Laws to each object
- Solve the equations

Multiple Objects – Example, cont.



Forces of Friction

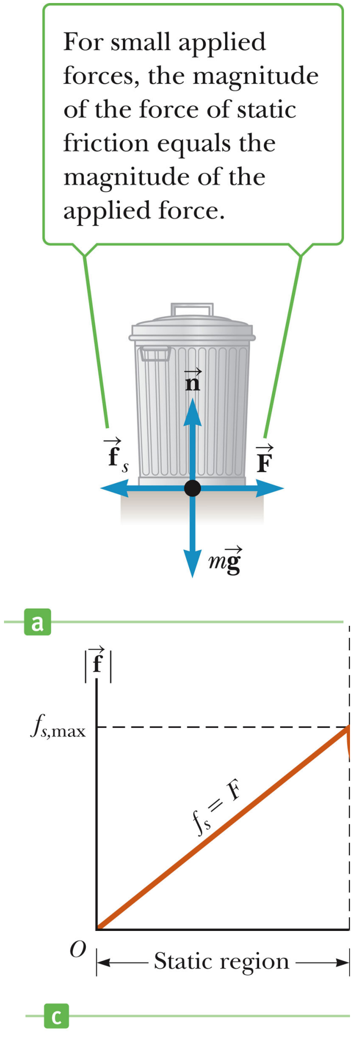
- When an object is in motion on a surface or through a viscous medium, there will be a resistance to the motion
  - This is due to the interactions between the object and its environment
- This is resistance is called **friction**

More About Friction

- Friction is proportional to the normal force
- 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
- The direction of the frictional force is opposite the direction of motion
- The coefficients of friction are nearly independent of the area of contact

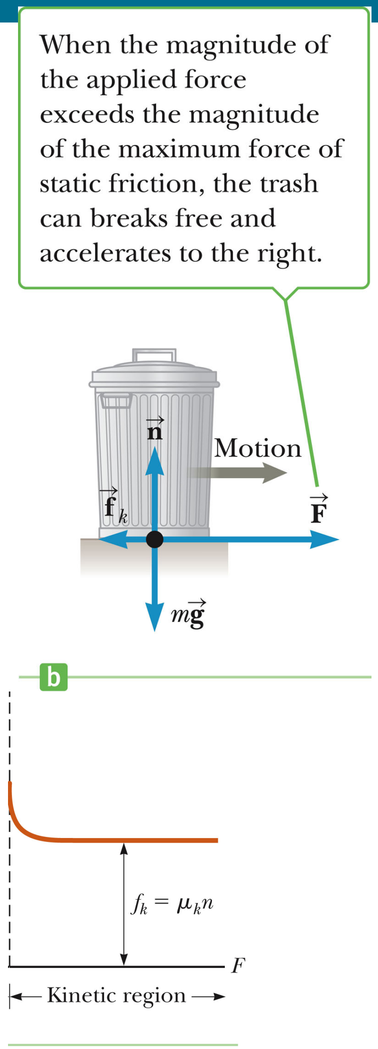
Static Friction, f_s

- Static friction acts to keep the object from moving
- If F increases, so does f_s
- If F decreases, so does f_s
- $f_s \le \mu_s n$
  - Use = sign for impending motion only



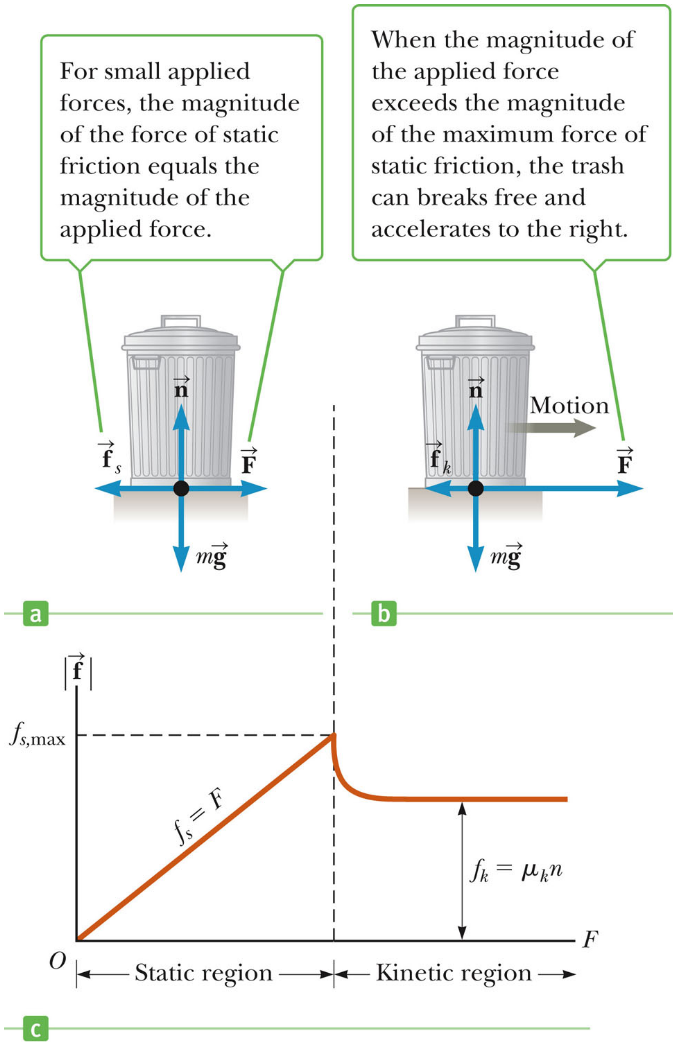
Kinetic Friction, f_k

- The force of kinetic friction acts when the object is in motion
- $f_k = \mu_k n$
  - Variations of the coefficient with speed will be ignored



Friction, final

- Adjust the force and see where you are on the graph
- Note especially where $f = F_s$



Some Coefficients of Friction

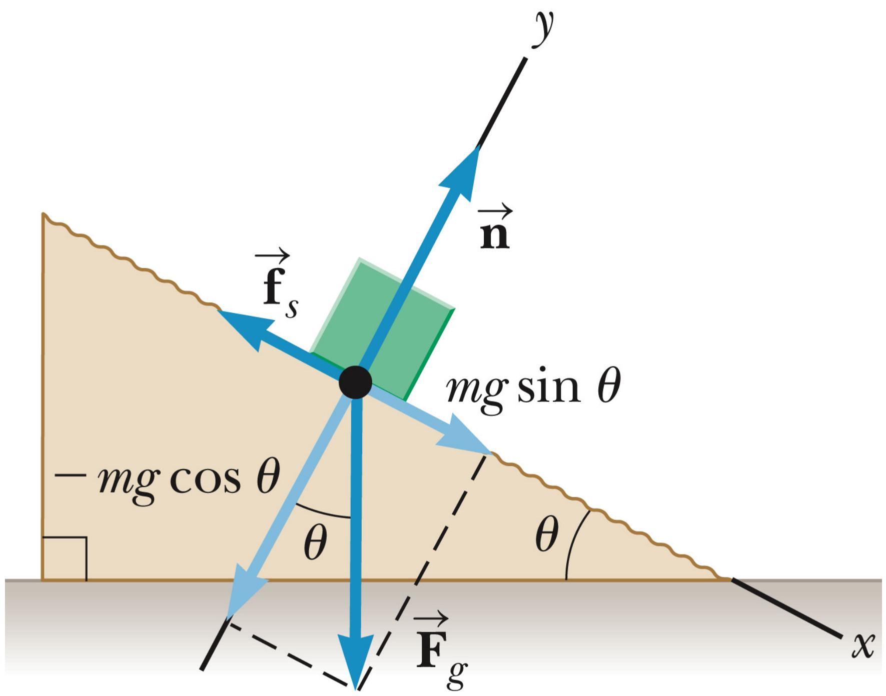
Table 4.2 Coefficients of Friction[a]

	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.

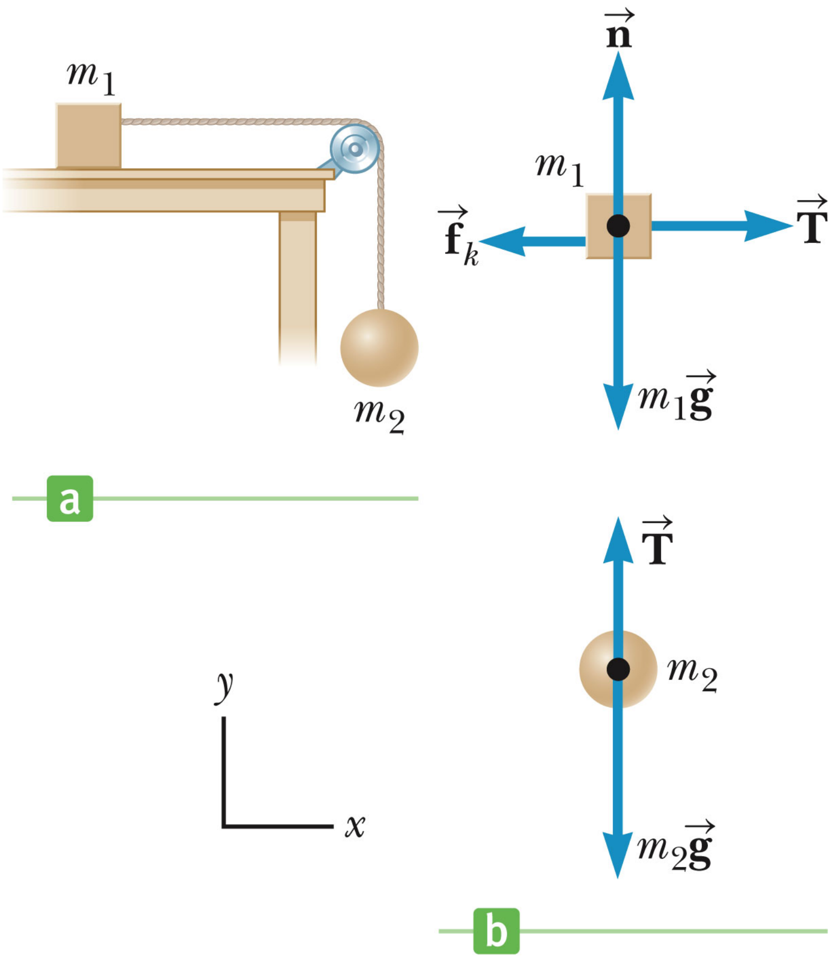
Block on a Ramp, Example with Friction

- Axes are rotated as usual on an incline
- The direction of impending motion would be down the plane
- Friction acts up the plane
  - Opposes the motion
- Apply Newton's Laws and solve equations



Connected Objects

- Apply Newton's Laws separately to each object
- The magnitude of the acceleration of both objects will be the same
- The tension is the same in each diagram
- Solve the simultaneous equations



Connected Objects – System Approach

- Treating the system as one object allows an alternative method or a check
  - Use only external forces
    - Not the tension – it's internal
  - The mass is the mass of the system
- Doesn't tell you anything about any internal forces

Other Types of Friction

- Friction between the moving car's wheels and the road is static friction
  - Unless the car is skidding
- Also have the air resistance, $\vec{\mathbf{R}}$