Quick Quiz 1 If a car is traveling eastward and slowing down, what is the direction of the force on the car that causes it to slow down? (a) eastward (b) westward (c) neither of these.

Quick Quiz 2 A ball is thrown upward. While the ball is in free fall, does its acceleration (a) increase (b) decrease (c) increase and then decrease (d) decrease and then increase (e) remain constant?

Quick Quiz 3 After a ball is thrown upward and is in the air, its speed (a) increases (b) decreases (c) increases and then decreases (d) decreases and then increases (e) remains the same.

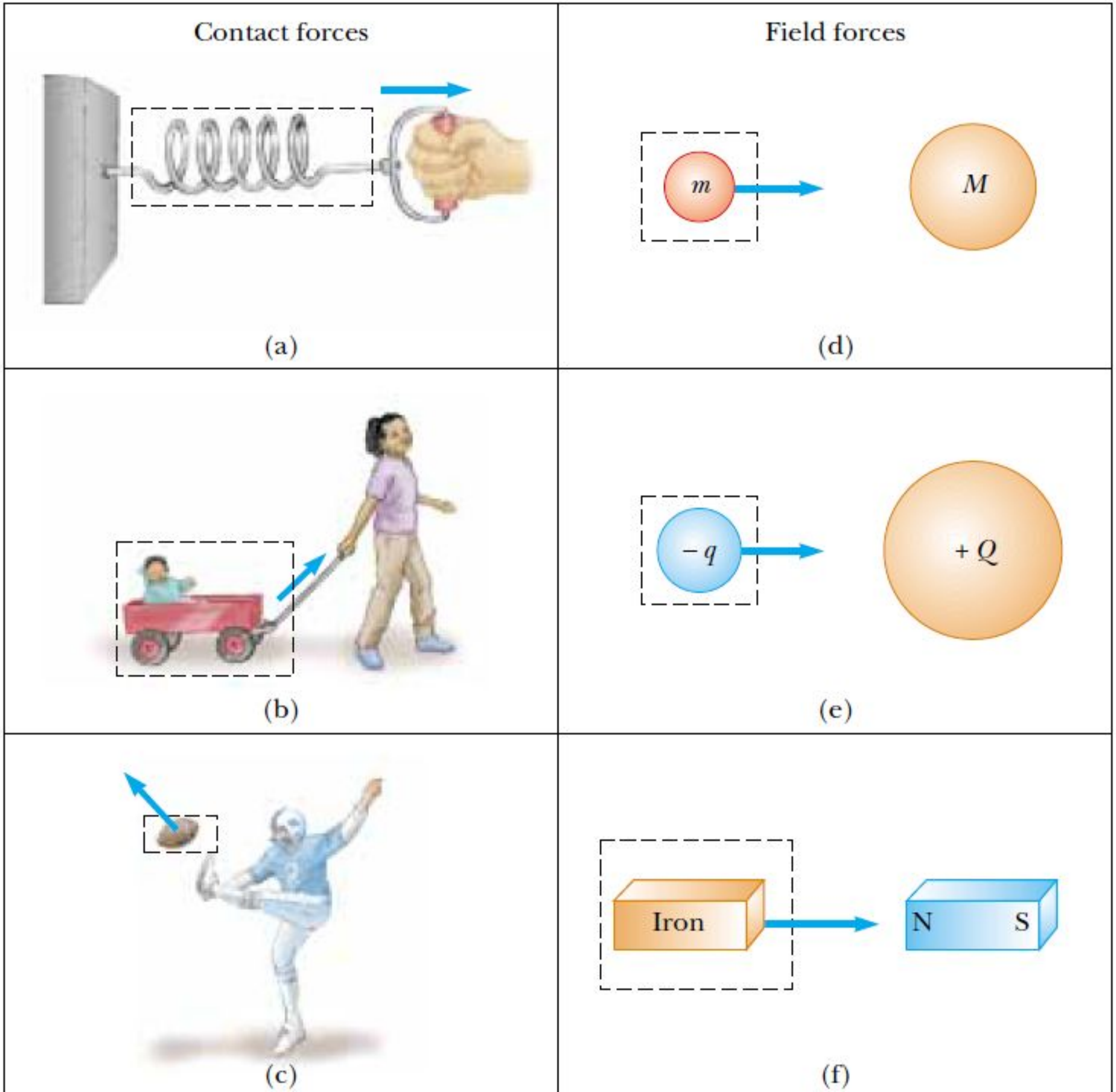
Course of lectures «Contemporary Physics: Part1»

Lecture №3

Dynamics of mas point and rigid body. Newton’s laws. Mass. Force. Forces in mechanics. Gravitational forces. The law of gravity. Elastic forces. Friction forces. Circular Motion and Other Applications of Newton’s Laws.

Previously we described motion in terms of position, velocity, and acceleration without considering what might cause that motion. Now we consider the cause—what might cause one object to remain at rest and another object to accelerate? The two main factors we need to consider are the forces acting on an object and the mass of the object. We discuss the three basic laws of motion, which deal with forces and masses and were formulated more than three centuries ago by Isaac Newton. Once we understand these laws, we can answer such questions as “What mechanism changes motion?” and “Why do some objects accelerate more than others?”

contact forces



field forces

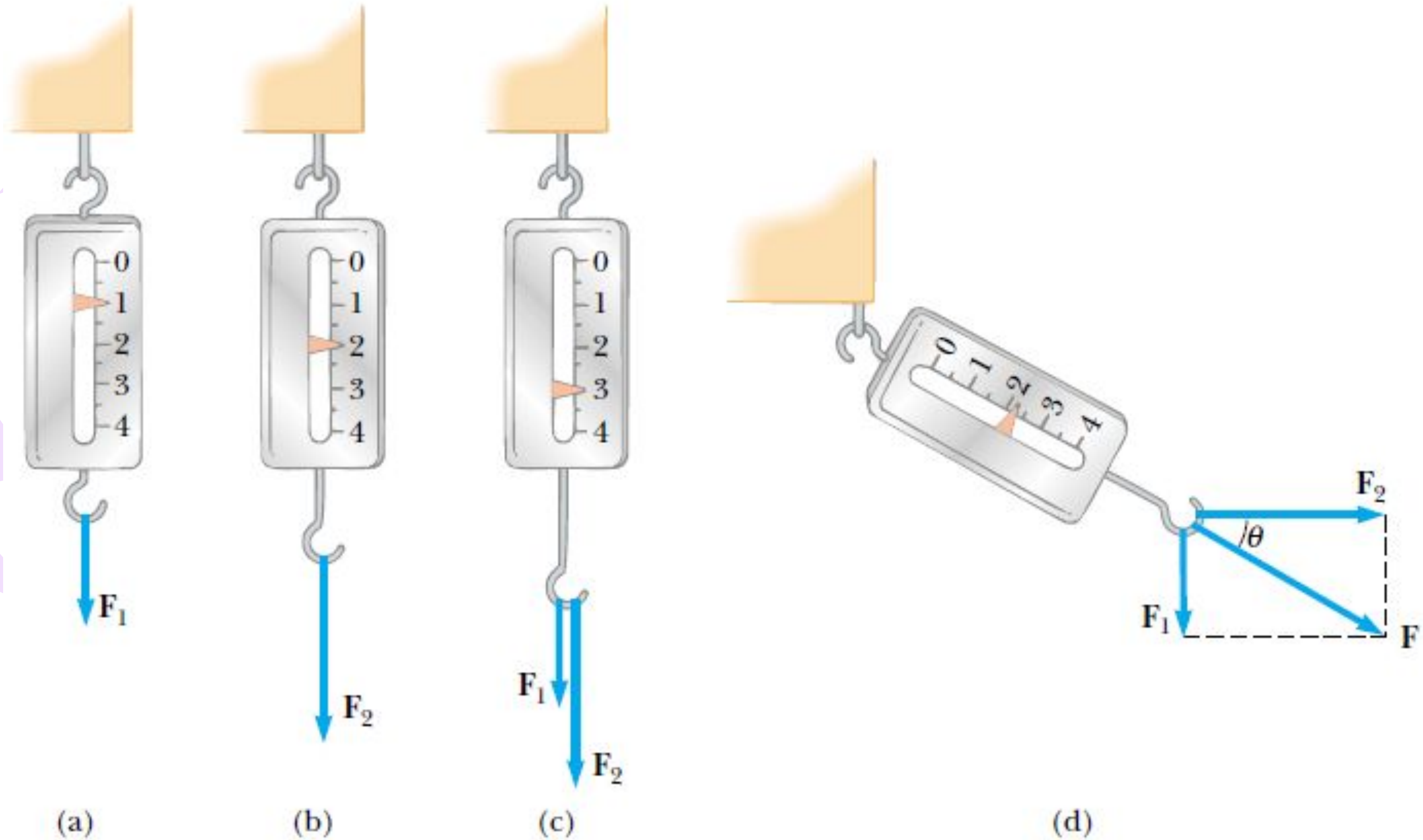
The Concept of Force

The only known *fundamental* forces in nature are all field forces:

(1) gravitational forces between objects,
(2) electromagnetic forces between electric charges,
(3) nuclear forces between subatomic particles, and
(4) *weak forces* that arise in certain radioactive decay processes.

In classical physics, we are concerned only with gravitational and electromagnetic forces.

The Concept of Force



Newton’s First Law and Inertial Frames

Moving object can be observed from any number of reference frames. Newton’s first law of motion, sometimes called the *law of inertia*, defines a special set of reference frames called *inertial frames. This law can be stated as* follows:

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

Newton’s First Law and Inertial Frames

Such a reference frame is called an inertial frame of reference.

Any reference frame that moves with constant velocity relative to an inertial frame is itself an inertial frame.

Newton's First Law and Inertial Frames

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 (that is, with a constant speed in a straight line).

When no force acts on an object, the acceleration of the object is zero.

Mass

Mass is that property of an object that specifies how much resistance an object exhibits to changes in its velocity, and the SI unit of mass is the kilogram. The greater the mass of an object, the less that object accelerates under the action of a given applied force.

Mass

To describe mass quantitatively, we begin by experimentally comparing the accelerations a given force produces on different objects. Suppose a force acting on an object of mass *m_1 produces an acceleration* ***a_1, and the same force acting on an object of mass*** *m_2 produces an acceleration* ***a_2. The ratio of the two masses is defined as the inverse ratio*** of the magnitudes of the accelerations produced by the force:

$$\frac{m_1}{m_2} \equiv \frac{a_2}{a_1} \qquad \textbf{(2.1)}$$

Mass

Mass is an inherent property of an object and is independent of the object's surroundings and of the method used to measure it.

Also, **mass is a scalar** quantity and thus obeys the rules of ordinary arithmetic. That is, several masses can be combined in simple numerical fashion. For example, if you combine a 3-kg mass with a 5-kg mass, the total mass is 8 kg. We can verify this result experimentally by comparing the accelerations that a known force gives to several objects separately with the acceleration that the same force gives to the same objects combined as one unit.

Mass

Mass should not be confused with weight. **Mass and weight are two different quantities.** The weight of an object is equal to the magnitude of the gravitational force exerted on the object and varies with location. For example, a person who weighs 180 lb on the Earth weighs only about 30 lb on the Moon. On the other hand, the mass of an object is the same everywhere: an object having a mass of 2 kg on the Earth also has a mass of 2 kg on the Moon.

Newton's Second Law

Newton's first law explains what happens to an object when no forces act on it. It either remains at rest or moves in a straight line with constant speed. Newton's second law answers the question of what happens to an object that has a nonzero resultant force acting on it.

Newton's Second Law

Imagine performing an experiment in which you push a block of ice across a frictionless horizontal surface. When you exert some horizontal force **F** on the block, it moves with some acceleration **a.** If you apply a force twice as great, you find that the acceleration of the block doubles. If you increase the applied force to 3F, the acceleration triples, and so on. From such observations, we conclude that **the acceleration of an object is directly proportional to the force acting on it**.

Newton’s Second Law

The acceleration of an object also depends on its mass, as stated in the preceding section. We can understand this by considering the following experiment. If you apply a force **F** to a block of ice on a frictionless surface, the block undergoes some acceleration **a**. If the mass of the block is doubled, the same applied force produces an acceleration **a**/2. If the mass is tripled, the same applied force produces an acceleration **a**/3, and so on.

Newton's Second Law

According to this observation, we conclude that the magnitude of the acceleration of an object is inversely proportional to its mass. These observations are summarized in 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.

Newton's Second Law

Thus, we can relate mass, acceleration, and force through the following mathematical statement of Newton's second law:

$$\boxed{\sum \mathbf{F} = m\mathbf{a}} \qquad \textbf{(2.2)}$$

In both the textual and mathematical statements of Newton's second law above, we have indicated that the acceleration is due to the *net force* $\sum \mathbf{F}$ *acting on an object. The* net force on an object is the vector sum of all forces acting on the object. In solving a problem using Newton's second law, it is imperative to determine the correct net force on an object. There may be many forces acting on an object, but there is only one acceleration.

Unit of Force

The SI unit of force is the newton, which is defined as the force that, when acting on an object of mass 1 kg, produces an acceleration of 1 m/s^2. From this definition and Newton's second law, we see that the newton can be expressed in terms of the following fundamental units of mass, length, and time:

$$1\,\text{N} \equiv 1\,\text{kg} \cdot \text{m/s}^2 \qquad \textbf{(2.3)}$$

The Gravitational Force and Weight

We are well aware that all objects are attracted to the Earth. The attractive force exerted by the Earth on an object is called the **gravitational force** $\mathbf{F}_g$. This force is directed toward the center of the Earth,[3] and its magnitude is called the **weight** of the object.

We saw in Section 2.6 that a freely falling object experiences an acceleration $\mathbf{g}$ acting toward the center of the Earth. Applying Newton's second law $\Sigma\mathbf{F} = m\mathbf{a}$ to a freely falling object of mass m, with $\mathbf{a} = \mathbf{g}$ and $\Sigma\mathbf{F} = \mathbf{F}_g$, we obtain

$$\mathbf{F}_g = m\mathbf{g} \qquad (2.4)$$

Thus, the weight of an object, being defined as the magnitude of $\mathbf{F}_g$, is equal to mg.

The Gravitational Force and Weight

Because it depends on g, weight varies with geographic location. Because g decreases with increasing distance from the center of the Earth, objects weigh less at higher altitudes than at sea level. For example, a 1 000-kg palette of bricks used in the construction of the Empire State Building in New York City weighed 9 800 N at street level, but weighed about 1 N less by the time it was lifted from sidewalk level to the top of the building. As another example, suppose a student has a mass of 70.0 kg. The student's weight in a location where $g = 9.80\ \mathrm{m/s^2}$ is $F_g = mg = 686$ N (about 150 lb). At the top of a mountain, however, where $g = 9.77\ \mathrm{m/s^2}$, the student's weight is only 684 N. Therefore, if you want to lose weight without going on a diet, climb a mountain or weigh yourself at 30 000 ft during an airplane flight!

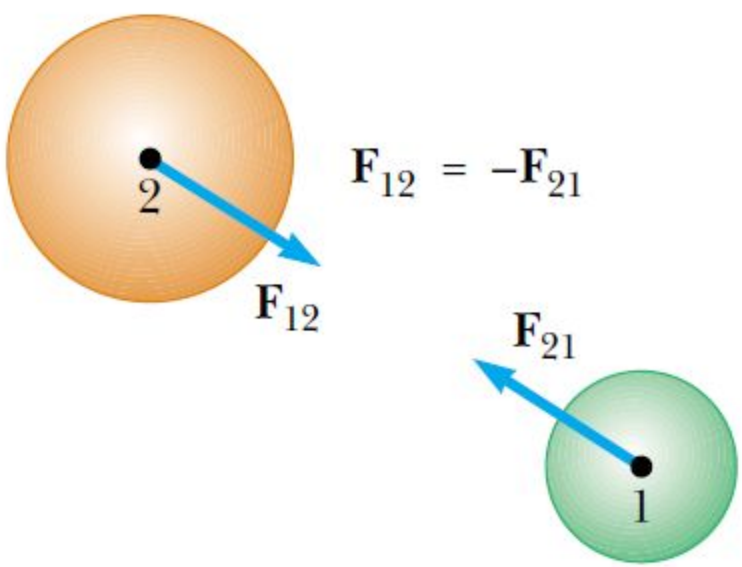
Newton’s Third Law

If you press against a corner of this textbook with your fingertip, the book pushes back and makes a small dent in your skin. If you push harder, the book does the same and the dent in your skin is a little larger. This simple experiment illustrates a general principle of critical importance known as **Newton’s third law**:

If two objects interact, the force F_{12} exerted by object 1 on object 2 is equal in magnitude and opposite in direction to the force F_{21} exerted by object 2 on object 1:

$$\mathbf{F}_{12} = -\mathbf{F}_{21} \qquad \textbf{(2.5)}$$

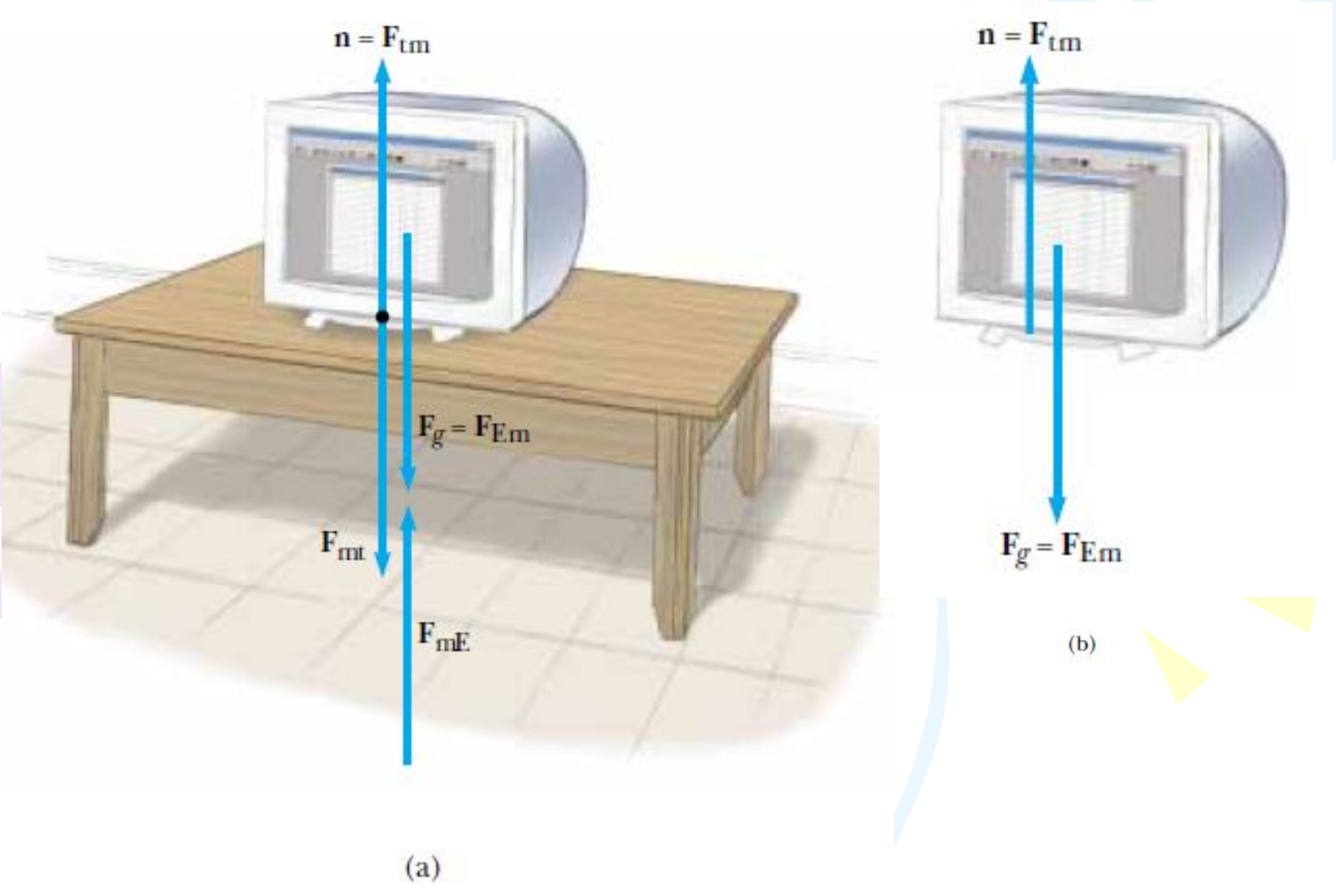
Newton's Third Law



Forces always occur in pairs, or that a single isolated force cannot exist. The force that object 1 exerts on object 2 may be called the *action force* and the force of object 2 on object 1 the *reaction force*. In reality, either force can be labeled the action or reaction force.

The action force is equal in magnitude to the reaction force and opposite in direction. In all cases, the action and reaction forces act on different objects and must be of the same type.

Newton’s Third Law



Newton's Third Law

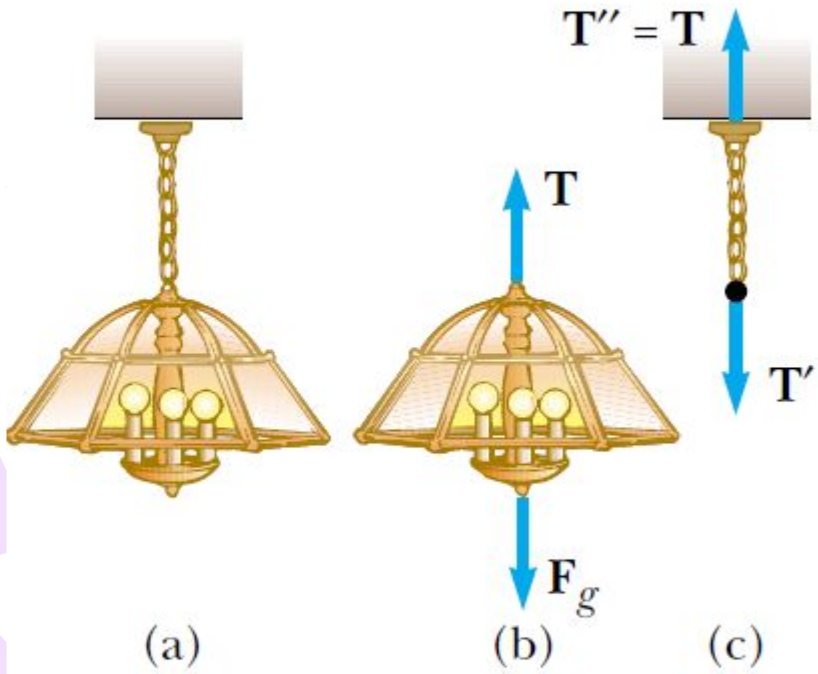
When we apply Newton's laws to an object, we are interested only in external forces that act on the object.

For now, we also neglect the effects of friction in those problems involving motion; this is equivalent to stating that the surfaces are *frictionless.*

In problem statements, the synonymous terms *light* and *of negligible mass* are used to indicate that a mass is to be ignored when you work the problems. When a rope attached to an object is pulling on the object, the rope exerts a force T on the object, and the magnitude *T* of that force is called the tension in the rope. Because it is the magnitude of a vector quantity, tension is a scalar quantity.

Newton's Third Law

Objects in Equilibrium



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

$$\mathbf{a} = 0,$$

$$\Sigma F_x = 0$$

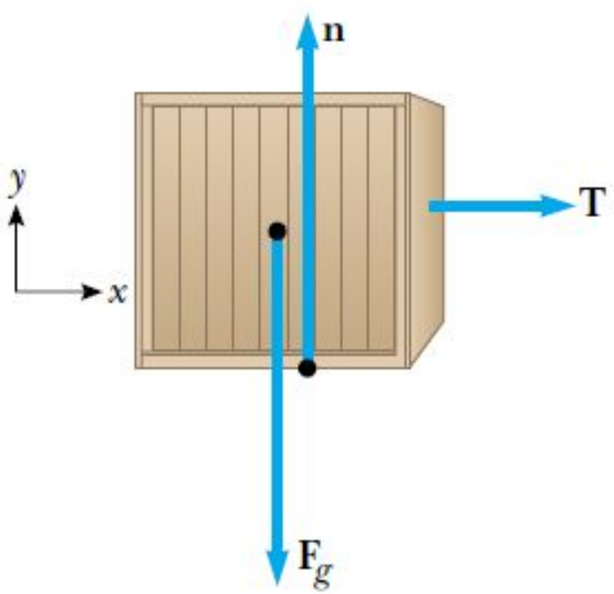
$$\Sigma F_y = ma_y = 0 \text{ gives}$$

$$\sum F_y = T - F_g = 0 \quad \text{or} \quad T = F_g$$

Newton's Third Law

Objects Experiencing a Net Force

(a)



(b)

$$\sum F_x = ma_x$$

$$\sum F_x = T = ma_x \quad \text{or} \quad a_x = \frac{T}{m}$$

$$\sum F_y = ma_y \text{ with } a_y = 0$$

$$n + (-F_g) = 0 \quad \text{or} \quad n = F_g$$

$a_x = T/m =$ **constant**

$$v_{xf} = v_{xi} + \left(\frac{T}{m}\right)t$$

$$x_f = x_i + v_{xi}t + \frac{1}{2}\left(\frac{T}{m}\right)t^2$$

Forces of Friction

Actions of bodies to each other, making the accelerations, called ***forces***. All forces can be divided to 2 main types: forces, acting *at the direct* contact, and forces, acting independently whether bodies contact or not, i.e. forces, which can act ***on the distance***.

Compressions, tensions, flexions etc. are the form or volume change in compare to its initial state. Such changes are called ***deformations***.

Forces, disappearing with disappearing of deformations, called ***elastic forces***.

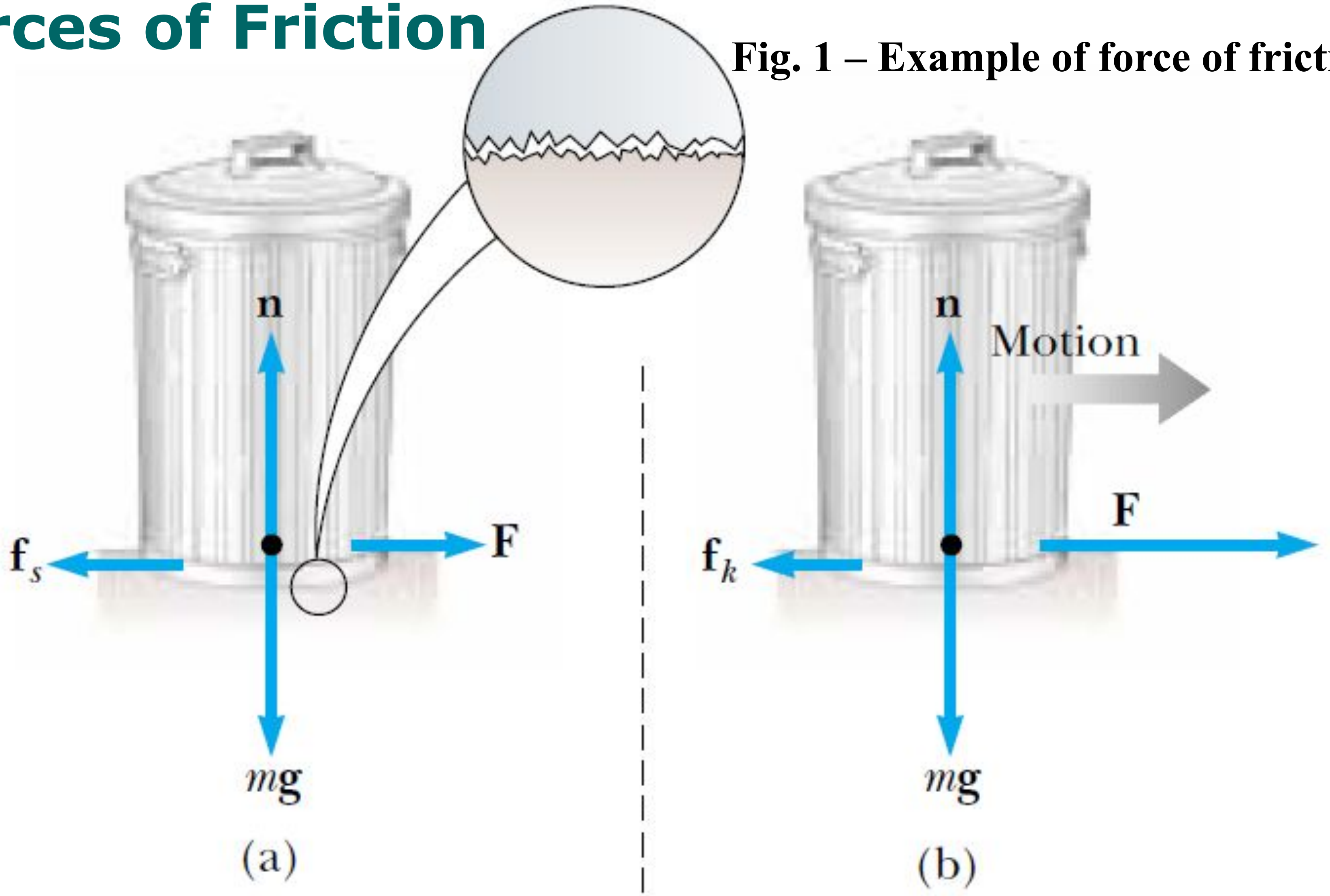
Forces of Friction

Except elastic forces at the direct contact can appear forces of another type so called ***forces of friction***.

The main feature of forces of friction is that they prevent the movement of every of contact bodies respectively to another one or prevent appearing of this movement.

Forces of Friction

Fig. 1 – Example of force of friction



The force that counteracts **F** and keeps the trash can from moving acts to the left and is called the **force of static friction f**$_s$. *As long as the trash can is not* moving, $f_s = F$.

Forces of Friction

At the same time with changing of direction of force **F** the direction of force of friction also changes. Thus module and direction of force of friction are defined by module and direction of that external force, which it balanced: ***force of static friction equals on module and opposite to direction of that external force, which approaches to cause the slipping of one body on another one.***

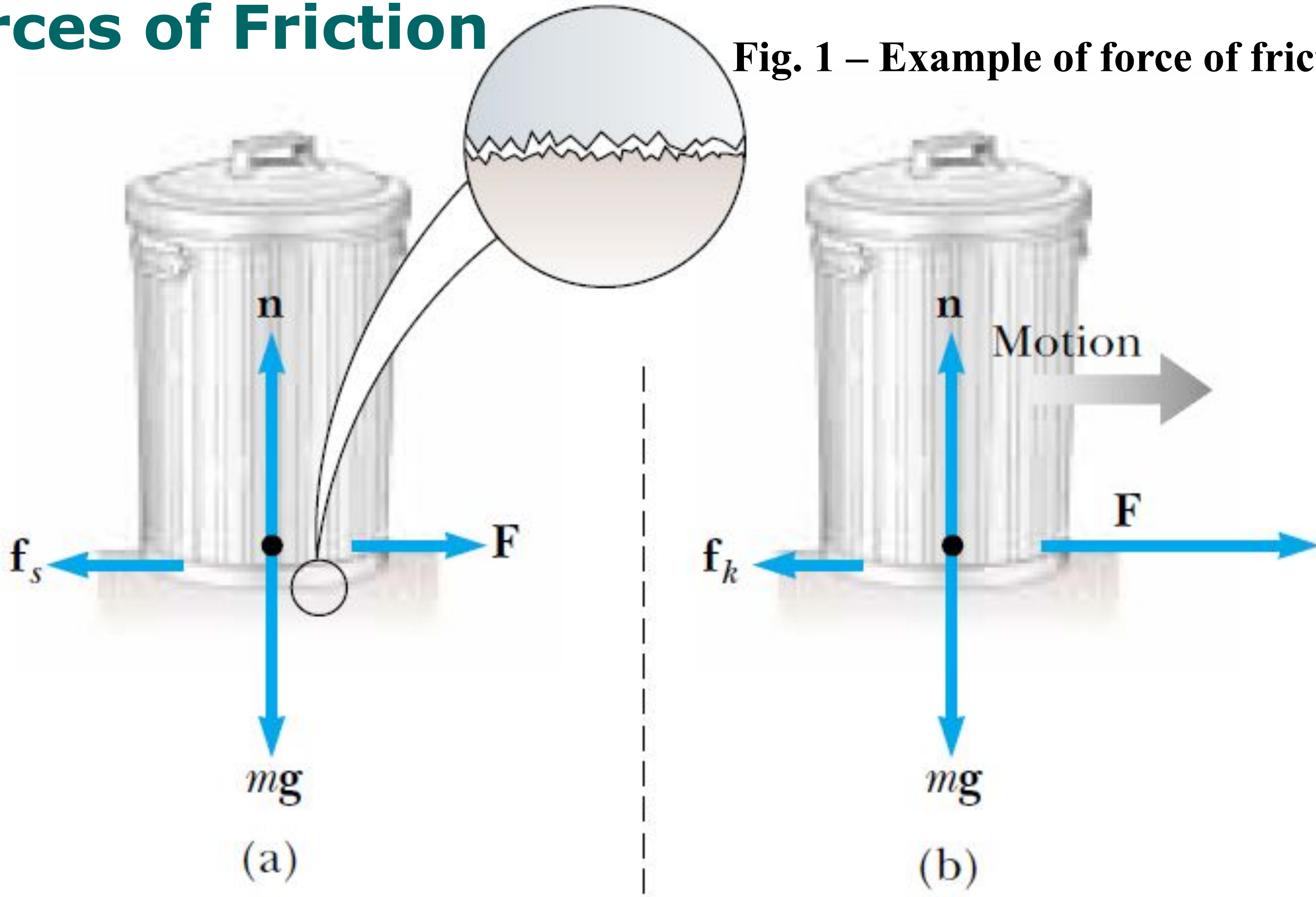
The magnitude of the force of static friction between any two surfaces in contact can have the values

$$\boxed{f_s \leq \mu_s n} \qquad \textbf{(2.6)}$$

where the dimensionless constant μ_s *is called the coefficient of static friction and n is the magnitude of the normal force exerted by one surface on the other.*

Forces of Friction

Fig. 1 – Example of force of friction



We call the friction force for an object in motion the force of kinetic friction $\mathbf{f}_k$.

The magnitude of the force of kinetic friction acting between two surfaces is

$$\boxed{f_k = \mu_k n} \qquad \textbf{(2.7)}$$

where μ_k *is the coefficient of kinetic friction.*

Table 1. Coefficients of Friction

	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

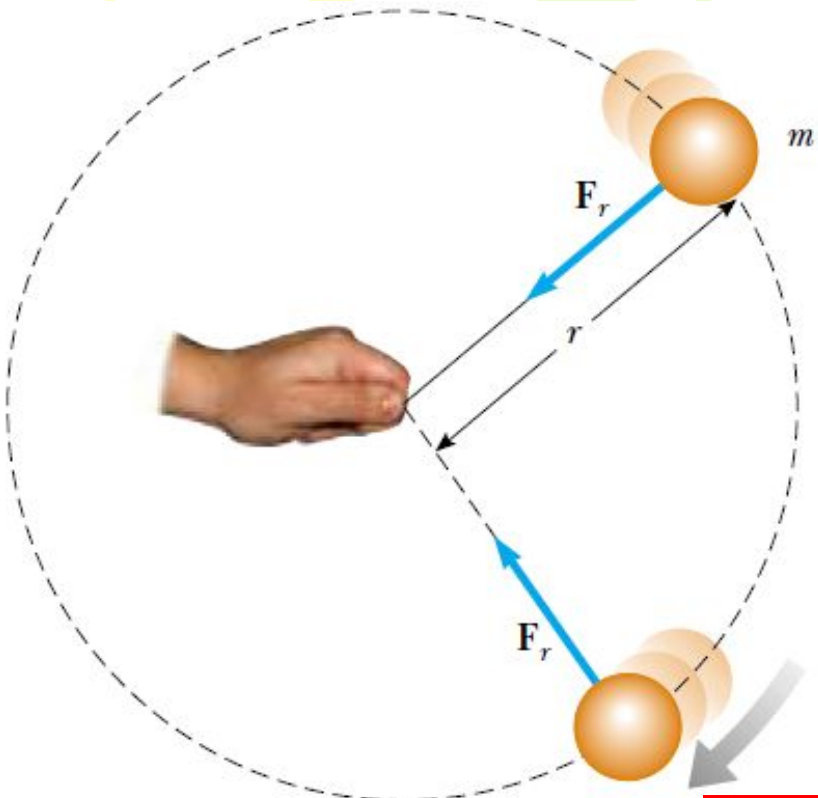
Newton's Second Law Applied to Uniform Circular Motion

A particle moving with uniform speed v in a circular path of radius r experiences an acceleration that has a magnitude:

$$\boxed{a_c = \frac{v^2}{r}}$$

The acceleration is called *centripetal acceleration* because $\boldsymbol{a_c}$ is directed toward the center of the circle. Furthermore, $\boldsymbol{a_c}$ is always perpendicular to **v**.

Figure 2. Overhead view of a ball moving in a circular path in a horizontal plane. A force $\mathbf{F_r}$ directed toward the center of the circle keeps the ball moving in its circular path.



If we apply Newton's second law along the radial direction, we find that the net force causing the centripetal acceleration can be evaluated:

$$\boxed{\sum F = ma_c = m\frac{v^2}{r}} \quad \textbf{(2.8)}$$

Nonuniform Circular Motion

If a particle moves with varying speed in a circular path, there is, in addition to the radial component of acceleration, a tangential component having magnitude *dv/dt*. Therefore, the force acting on the particle must also have a tangential and a radial component. Because the total acceleration is

$$\boxed{\mathbf{a} = \mathbf{a}_r + \mathbf{a}_t}$$

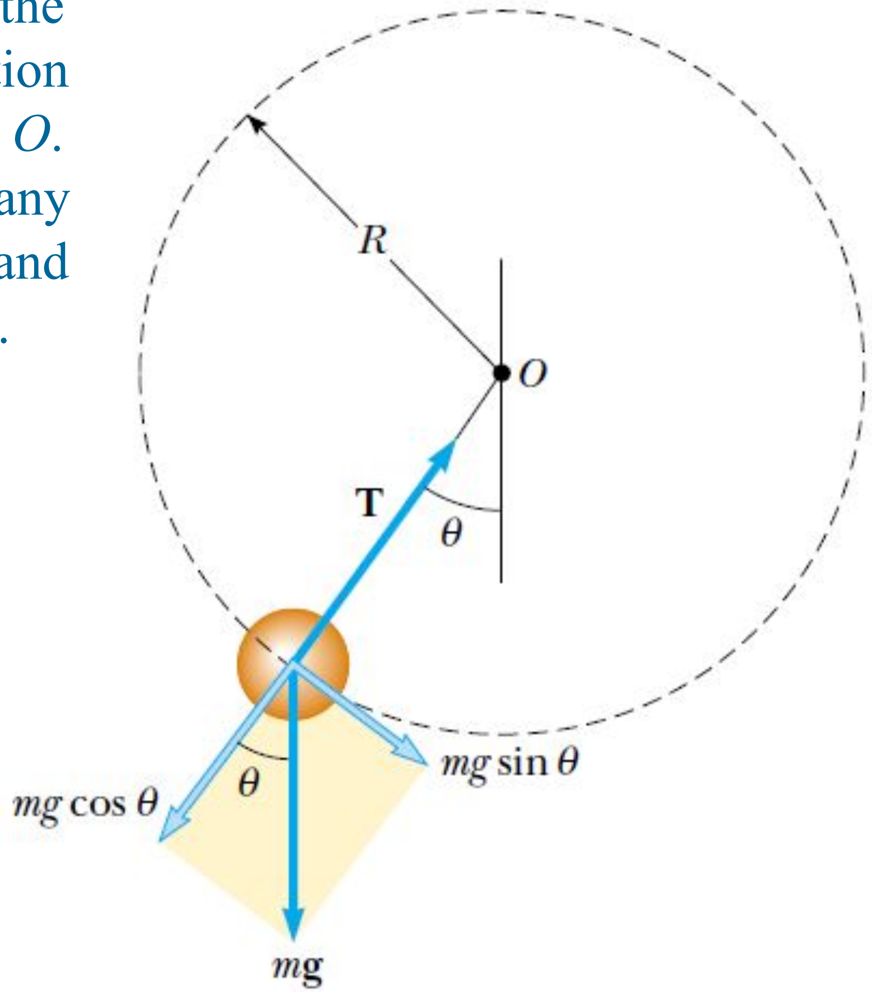
the total force exerted on the particle is

$$\boxed{\sum \mathbf{F} = \sum \mathbf{F}_r + \sum \mathbf{F}_t} \qquad \textbf{(2.9)}$$

The $\sum \mathbf{F}_r$ vector is directed toward the center of the circle and is responsible for the centripetal acceleration. The vector $\sum \mathbf{F}_r$ tangent to the circle is responsible for the tangential acceleration, which represents a change in the speed of the particle with time.

Nonuniform Circular Motion

A small sphere of mass m is attached to the end of a cord of length R and set into motion in a vertical circle about a fixed point O. Determine the tension in the cord at any instant when the speed of the sphere is v and the cord makes an angle θ with the vertical.



$$\sum F_t = mg \sin\theta = ma_t$$

$$a_t = g\sin\theta$$

$$\sum F_r = T - mg\cos\theta = \frac{mv^2}{R}$$

$$T = \boxed{m\left(\frac{v^2}{R} + g\cos\theta\right)}$$

Motion in Accelerated Frames

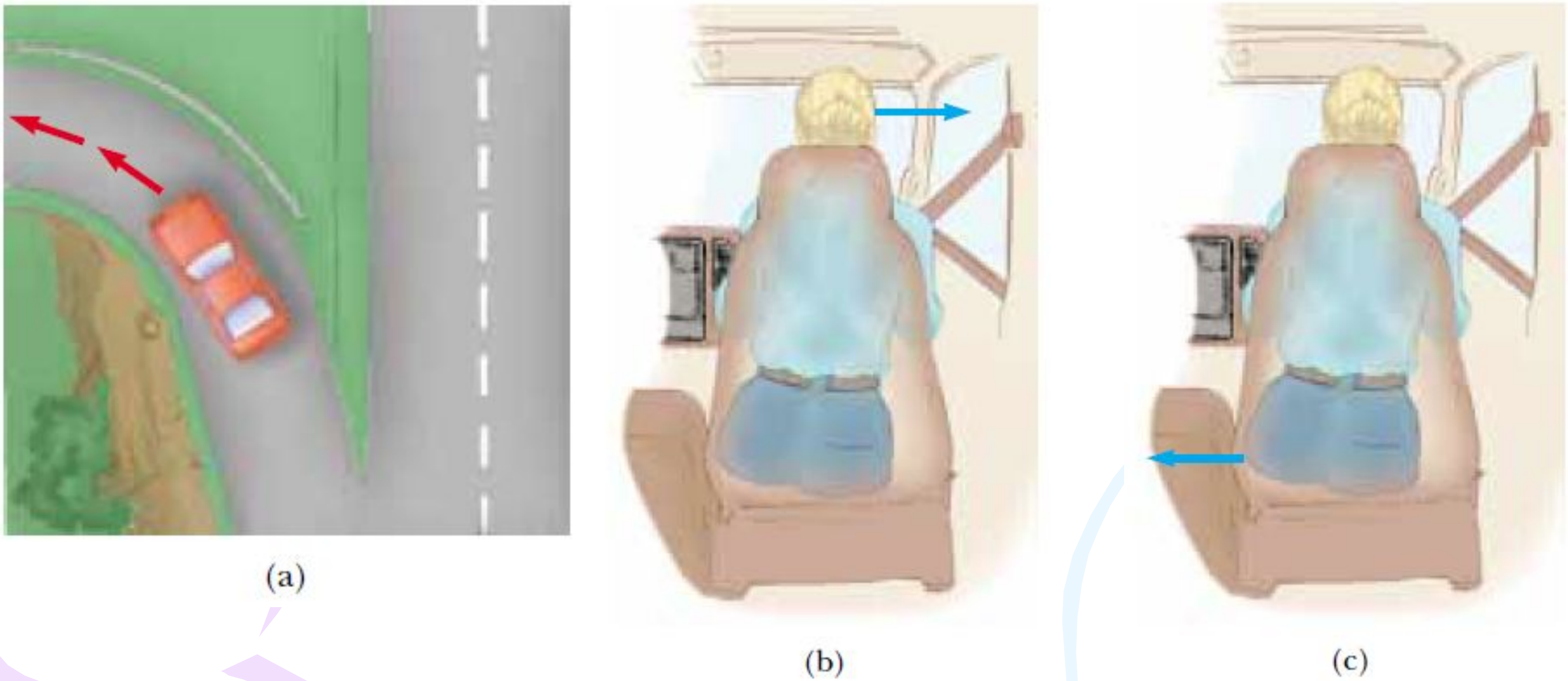


Figure 3. (a) A car approaching a curved exit ramp. What causes a front-seat passenger to move toward the right-hand door? (b) From the frame of reference of the passenger, a force appears to push her toward the right door, but this is a fictitious force. (c) Relative to the reference frame of the Earth, the car seat applies a leftward force to the passenger, causing her to change direction along with the rest of the car.

Motion in Accelerated Frames

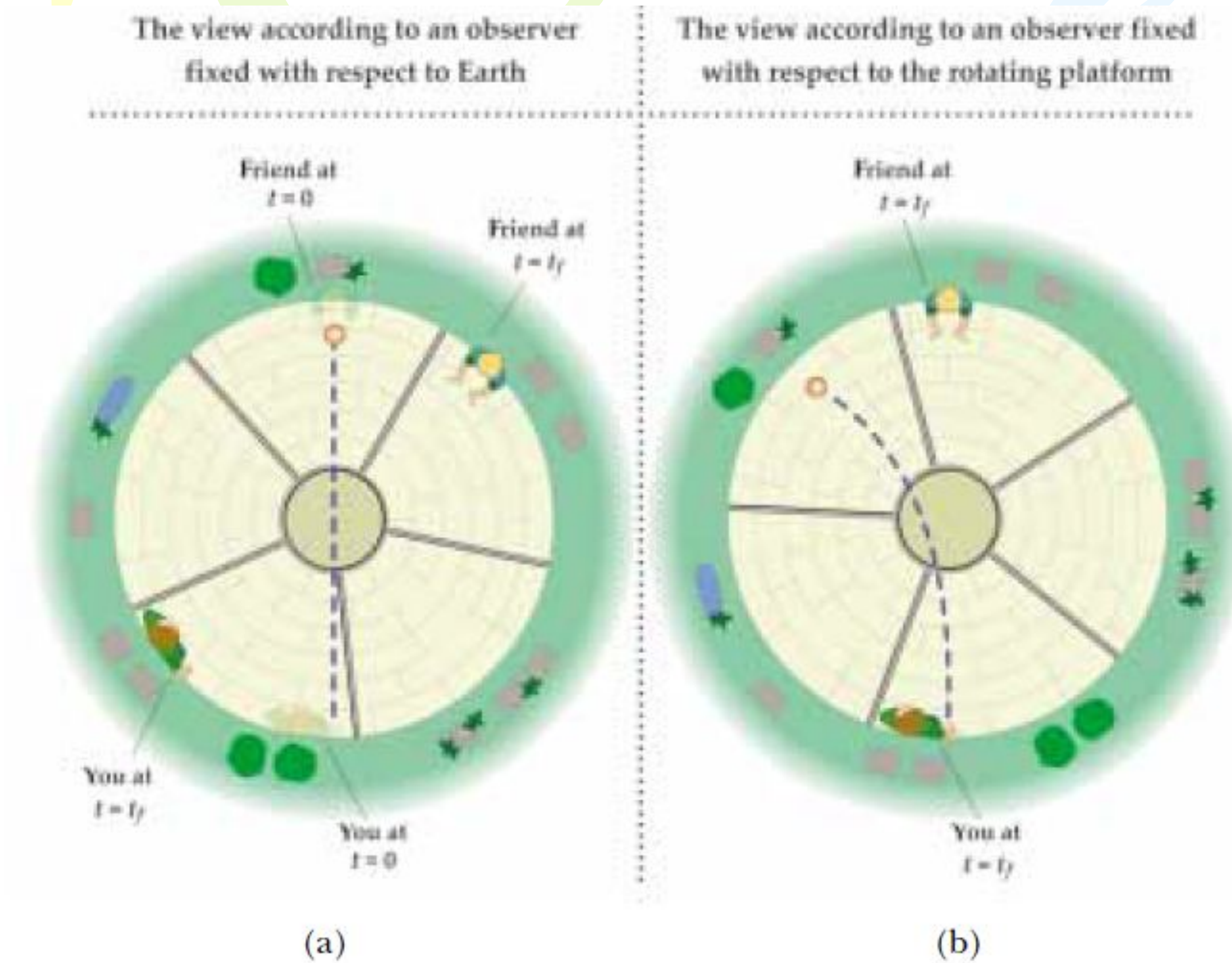


Figure 4.

Quick Quiz 1 If a fly collides with the windshield of a fast-moving bus, which object experiences an impact force with a larger magnitude? (a) the fly (b) the bus (c) the same force is experienced by both.

Quick Quiz 2 In a free-body diagram for a single object, you draw (a) the forces acting on the object and the forces the object exerts on other objects, or (b) only the forces acting on the object.

Quick Quiz 3 Which of the following is *impossible* for a car moving in a circular path? (a) the car has tangential acceleration but no centripetal acceleration. (b) the car has centripetal acceleration but no tangential acceleration. (c) the car has both centripetal acceleration and tangential acceleration.