

# PS113 Chapter 4

## Forces and Newton's laws of motion

### 1 The concepts of force and mass

- A force is described as the “push” or “pull” between two objects
- There are two kinds of forces
  1. **Contact forces** where two objects exert their force upon each other through physical contact, and
  2. **Action-at-a-distance forces** where physical contact is not required to exert a force (e.g., gravity). These forces are described by introducing a new concept called “the field.”
- The word **mass** is usually used to describe objects of varying weights. We will see that mass plays an important role in the dynamical motion of objects. The “mass of an object” is related to how easy or difficult it is to set it into motion.

## 2 Newton's first law of motion

- **Newton's first law:** An object continues in a state of rest or in a state of motion at a constant speed along a straight line, unless compelled to change that state by a net force.
- The “net force” is the vector sum of all the forces acting on an object.
- Examples where the “net force” is zero (or approximately zero), include
  1. the motion of a hockey puck on ice,
  2. a car rolling down the road without friction, and
  3. a spaceship in the vacuum of space with its engines turned off (i.e., no thrust).
- **Definition of inertia and mass:** Inertia is the natural tendency of an object to remain at rest or in motion at a constant speed along a straight line. The mass of an object is a quantitative measure of its inertia (i.e., it has so many kilograms of mass).  
**The SI units of inertia and mass:** kilogram (kg)

The more mass an object has, the more difficult it is to change its velocity, that is, the more difficult it is to accelerate it.  $\bar{\mathbf{a}} = \Delta \mathbf{v} / \Delta t$

- **Definition of an inertial reference frame:** An inertial reference frame is one in which Newton's law of inertia is valid ( $\Sigma F = 0$ )

### 3 Newton's second law of motion

- When an object is at rest, it will remain at rest until acted upon by a force (or forces) such that  $\Sigma F \neq 0$ .
- **Newton's second law:** When a net external force  $\Sigma \mathbf{F}$  acts on an object of mass  $m$ , the acceleration  $\mathbf{a}$  that results is directly proportional to the net force and has a magnitude that is inversely proportional to the mass. The direction of the acceleration is the same as the direction of the net force.

$$\mathbf{a} = \frac{\Sigma \mathbf{F}}{m} \quad \text{or} \quad \Sigma \mathbf{F} = m\mathbf{a}$$

The **SI unit of force:**  $\text{kg}\cdot\text{m}/\text{s}^2 = \text{newton (N)}$

- Units of mass, acceleration, and force in SI, CGS, and BE.

**Problem 6:** Scientists are experimenting with a kind of gun that may eventually be used to fire payloads directly into orbit. In one test, this gun accelerates a 5.0-kg projectile from rest to a speed of  $4.0 \times 10^3$  m/s. The net force accelerating the projectile is  $4.9 \times 10^5$  N. How much time is required for the projectile to come up to speed?      Answer: 0.041 sec    or    41 ms

### 4 The vector nature of Newton's second law of motion

- The vector equation  $\Sigma \mathbf{F} = m\mathbf{a}$  can be written as two scalar equations:

$$\Sigma F_x = ma_x \quad \text{and} \quad \Sigma F_y = ma_y$$

- The accelerations  $a_x$  and  $a_y$  can be solved for separately and used in the four *equations of motion* developed in the previous chapter.

**Problem 11:** Only two forces (40.0 N in the  $x$  direction and 60.0 N @  $45.0^\circ$ ) act on an object (mass = 3.00 kg), as shown in the drawing. Find the magnitude and direction (relative to the  $x$  axis) of the acceleration of the object.

**Answers:** 30.9 m/s<sup>2</sup> and  $27.2^\circ$  above the  $+x$  axis.

**Problem 15:** When a parachute opens, the air exerts a large drag force on it. This upward force is initially greater than the weight of the sky diver and, thus, slows him down. Suppose the weight of the sky diver is 915 N and the drag force has a magnitude of 1027 N. The mass of the sky diver is 93.4 kg. What are the magnitude and direction of his acceleration?

## 5 Newton's third law of motion

- All forces occur in pairs. There is no such thing as an isolated force.
- **Newton's third law of motion:**  
Whenever one body exerts a force on a second body, the second body exerts an oppositely directed force of equal magnitude on the first body.
- The force on object 1 due to object 2 ( $\mathbf{F}_{12}$ ) is equal and opposite to the force on object 2 due to object 1 ( $\mathbf{F}_{21}$ )

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

- Homework problems demonstrating the third law of motion will be forthcoming once we introduce a few more forces (gravity, normal force, etc.)

## 6 Types of forces: an overview

- There are four “known” fundamental forces in nature:
  1. Electricity and magnetism
  2. Gravity
  3. Weak (responsible for radioactive decays)
  4. Strong (responsible for holding protons and neutrons together in the nucleus)
- All the other “so called” forces described in this book (tension, friction, air-resistance, normal force, etc.) are manifestations of these fundamental forces.
- No homework problems covering this section.

## 7 The gravitational force

- Isaac Newton not only identified the minimal set of laws describing the motion of particles (Newton's three laws of motion), and invented a new branch of mathematics (calculus), he also developed the universal law of gravitation.
- **Newton's law of universal gravitation:** Every particle in the universe exerts an attractive force on every other particle. A particle is a piece of matter, small enough in size to be regarded as a mathematical point. For two particles, which have mass  $m_1$  and  $m_2$  and are separated by a distance  $r$ , the force that each exerts on the other is directed along the line joining the particles and has a magnitude given by

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

$G$  is the universal gravitational constant whose value is found experimentally to be  $G = 6.67259 \times 10^{-11} \text{ N}\cdot\text{m}^2/\text{kg}^2$

- **Definition of weight:** The weight of an object on the earth is the gravitational force that the earth exerts on the object. The weight always acts downward, toward the center of the earth. On another astronomical body, the weight is the gravitational force exerted on the object by that body.

**SI unit of weight:** newton (N)

- **On the surface of the earth,** the weight of an object can be calculated using Newton's law of universal gravitation:

$$W = G \frac{M_E m}{R_E^2} = mg \quad \text{where} \quad g = G \frac{M_E}{R_E^2} \approx 9.80 \text{ m/s}^2$$

- Problem 20:** A 5.0-kg rock and  $3.0 \times 10^{-4}$ -kg pebble are held near the surface of the earth. (a) Determine the magnitude of the gravitational force exerted on each by the earth. (b) Calculate the magnitude of the acceleration of each object when released.
- Problem 23:** A raindrop has a mass of  $5.2 \times 10^{-7}$  kg and is falling near the surface of the earth. Calculate the magnitude of the gravitational force exerted (a) on the raindrop by the earth and (b) on the earth by the raindrop.
- Problem 27:** Synchronous communications satellites are placed in circular orbit that is  $3.59 \times 10^7$  m above the surface of the earth. What is the magnitude of the acceleration due to gravity at this distance? **Answer:**  $0.223 \text{ m/s}^2$
- Problem 28:** The drawing shows one alignment of the sun, earth, and moon. The gravitational force  $\mathbf{F}_{\text{SM}}$  that the sun exerts on the moon is perpendicular to the force  $\mathbf{F}_{\text{EM}}$  that the earth exerts on the moon. The masses are: mass of sun =  $1.99 \times 10^{30}$  kg, mass of earth =  $5.98 \times 10^{24}$  kg, mass of moon =  $7.35 \times 10^{22}$  kg. The distances shown in the drawing are  $r_{sm} = 1.50 \times 10^{11}$  m and  $r_{em} = 3.85 \times 10^8$  m. Determine the magnitude of the net gravitational force on the moon. **Answer:**  $F = 4.77 \times 10^{20}$  N.

## 8 The normal force

- The normal force  $\mathbf{F}_N$  is one component of the force that a surface exerts on an object with which it is in contact, namely, the component that is perpendicular to the surface.

The normal force is generally written as:  $F_N = mg \cos \theta$

- **Apparent weight:** is the weight measured on a scale. It can be *less than* or *greater than* your “true” weight when you are in an accelerating system (e.g., an elevator).

$$\sum F_y = +F_N - mg = ma \quad \text{so} \quad F_N = ma + mg = m(a + g)$$

**Problem 42:** A woman stands on a scale in a moving elevator. Her mass is 60.0 kg, and the combined mass of the elevator and scale is an additional 815 kg. Starting from rest, the elevator accelerates upward. During the acceleration, the hoisting cable applies a force of 9410 N. What does the scale read during the acceleration?

**Answer:** apparent weight = 645 N



## 9 Static and kinetic frictional forces

- Another force that a surface can exert on an object with which it is in contact is friction. There are two kinds of friction (1) **static friction**, the friction force that occurs to keep an object from moving, and (2) **kinetic friction**, the friction force that occurs while an object is in motion.

1. **Static frictional force:** The magnitude  $f_s$  of the static frictional force can have any value from zero up to a maximum value of  $f_s^{max}$ , depending on the applied force. In other words,  $f_s \leq f_s^{max}$ . The equality holds only when  $f_s$  attains its maximum value, which is

$$f_s^{max} = \mu_s F_N$$

where  $\mu_s$  is the coefficient of static friction, and  $F_N$  is the magnitude of the normal force.

2. **Kinetic frictional force:** The magnitude  $f_k$  of the kinetic frictional force is given by

$$f_k = \mu_k F_N$$

where  $\mu_k$  is the coefficient of kinetic friction, and  $F_N$  is the magnitude of the normal force.

**Problem 46:** A cup of coffee is sitting on a table in an airplane that is flying at a constant altitude and a constant velocity. The coefficient of static friction between the cup and the table is 0.30. Suddenly, the plane accelerates, its altitude remaining constant. What is the maximum acceleration that the plane can have without the cup sliding backward on the table?

**Answer:** 2.94 m/s<sup>2</sup>

## 10 The tension force

- Most physics problems in the textbook involving tension have the following two properties:
  1. tension is the means by which a *pulling* force is communicated between two objects, and
  2. the “rope” or “string” connecting the two objects is massless, so the force is not diminished while the object(s) are in motion.

## 11 Equilibrium applications of Newton’s laws of motion

$\Sigma \mathbf{F} = \mathbf{0}$

- **Definition of equilibrium:** An object is in equilibrium when it has zero acceleration.

$$\Sigma F_x = 0 \quad \text{and} \quad \Sigma F_y = 0$$

### Reasoning strategies:

1. Identify the “system.”
2. Draw a free-body diagram showing all the *external forces* acting on the system.
3. Choose a set of  $x$ ,  $y$  axes for each object and resolve all the forces in the  $x$  and  $y$  directions.
4. Apply the equilibrium equations  $\Sigma F_x = 0$  and  $\Sigma F_y = 0$ .
5. Solve the two equations obtained in Step 4 for the desired unknown quantities, remembering that two equations can yield answers for only two unknowns at most.

**Problem 52:** The helicopter in the drawing is moving horizontally to the right at a constant velocity. The weight of the helicopter is  $W = 53,800$  N. The lift force  $\mathbf{L}$  generated by the rotating blades makes an angle of  $21.0^\circ$  with respect to the vertical. (a) What is the magnitude of the lift force? (b) Determine the magnitude of the air resistance  $\mathbf{R}$  that opposes the motion.

**Answers:**  $L = 57,628$  N      and       $R = 20,652$  N

## 12 Nonequilibrium applications of Newton's laws of motion

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

- In a **non-equilibrium** situation, an object has a non-zero acceleration, and Newton's  $2^{nd}$  law of motion must be used.

$$\Sigma F_x = ma \quad \text{and} \quad \Sigma F_y = ma$$

- Use the **reasoning strategies** from the previous sections to solve non-equilibrium problems; however, use Newton's  $2^{nd}$  law

$$\Sigma F_x = ma \quad \text{and} \quad \Sigma F_y = ma$$

in step 4.

**Problem 73:** Only two forces act on an object (mass = 4.00 kg), as shown in the drawing. Find the magnitude and direction (relative to the  $x$  axis) of the acceleration of the object. (Drawing: 60 N in the  $y$  direction and 40 N in the  $x$  direction)

**Problem 84:** A train consists of 50 cars, each of which has a mass of  $6.8 \times 10^3$  kg. The train has an acceleration of  $+8.0 \times 10^{-2}$  m/s<sup>2</sup>. Ignore the friction and determine the tension in the coupling (a) between the 30th and 31st cars, and (b) between the 49th and 50th cars.