Chapter 4

Newton's Laws of Motion

Topic	**Section**	**Test Your Understanding**	**In-class Problems** (Example)	**Assignment** (Exercise)
Newton's Laws of Motion: Force and Interactions, Newton's First Law, Newton's Second Law	4.1, 4.2,4.3	TYU-4.2 TYU-4.3	4.5,4.7	4.12,4.24, 4.30
Mass and Weight, Newton's third Law, Free Body Diagram	4.4, 4.5, 4.6	TYU-4.4		

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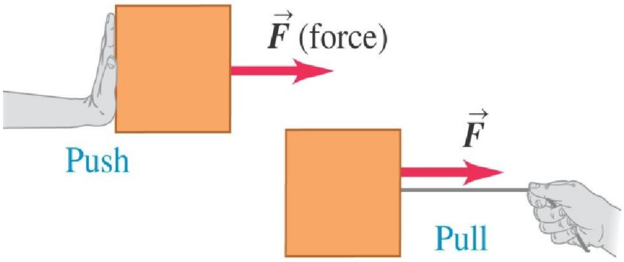
Force and interactions

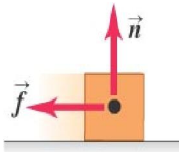
- A force is a push or a pull.
- A force is an interaction between two objects or between an object and its environment.
- A force is a vector quantity, with magnitude and direction.



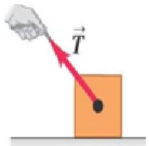
Four common types of forces

1. **Normal force:** When an object rests or pushes on a surface, the surface exerts a push on it that is directed perpendicular to the surface. This is a contact force.

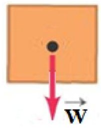
2. **Friction force:** In addition to the normal force, surfaces can resist motion along the surface. This is a contact force.



3. **Tension force:** When a force is exerted through a rope or cable, the force is transmitted through that rope or cable as a tension. This is a contact force.



4. **Weight:** It is Gravity's pull on an object. This is a long-range force, not a contact force, and is also a "field" force.



Newton's First Law of motion:

Unless and until an external force is applied, the object at rest tends to stay at rest and object in motion moves in constant velocity and zero acceleration.

When the net force applied on a body is zero, then the body is said to be in equilibrium and is called the balanced condition.

$$\sum \vec{F} = 0 \quad \text{Balanced (Equilibrium) condition}$$

$$\sum \vec{F} \neq 0 \quad \text{Unbalanced (Non-equilibrium) condition}$$

Newton's Second Law of motion:

Newton's 2nd law states that the rate of change of momentum is directly proportional to the applied force and act along the direction of the force.

$$F = \frac{dp}{dt} = \frac{d(mv)}{dt} = m\frac{dv}{dt} = m\,a$$

Where, dp = chance in momentum

p = mv = momentum of a moving body.

a = acceleration of the body.

In vector notation, the 2nd law can be written as $\sum \vec{F} = m\,\vec{a}$

In component form the law is:

$$\sum F_x = m\,a_x, \quad \sum F_y = m\,a_y, \quad \sum F_z = m\,a_z$$

- The equation is only valid if mass is constant.
- The equation is only valid in the inertial frame of reference

If the same net force is applied on two different bodies then the ratio of the masses is the inverse of the ratio of their acceleration.

$$F = m_1\,a_1 = m_2\,a_2$$

$$\Rightarrow \frac{m_1}{m_2} = \frac{a_2}{a_1}$$

Mass and weight:

- Mass characterizes the inertial properties of a body. The greater the mass, the greater the force needed to cause a given acceleration; $\sum \mathbf{F} = \mathbf{ma}$
- Weight is a force exerted on a body due to the pull of the earth. Bodies having large mass also have large weight. The force that makes the body accelerates downward at 9.8 m/s^2 is its weight.

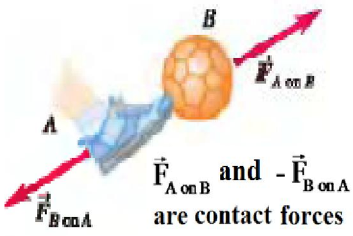
  A body with mass ***m*** has weight of magnitude of '**W**'. It is given by **W = mg**

  - ✓ The magnitude ***w*** of a body's weight is directly proportional to its mass ***m***.
  - ✓ The weight of a body is a force, a vector quantity,

$$\vec{W} = m\,\vec{g}$$

Newton's Third Law of motion:

To each and every action there exist an equal and opposite reaction.



- If you exert a force (action) on a body, the body always exerts a force (the "reaction") back upon you.
- A force (action) and its reaction force have the same magnitude but opposite in directions.
- Action and its reaction forces act on different bodies.

  If body A exerts a force $F_{A on B}$ on body B, then body B exerts a force $F_{B\ on\ A}$ on body A that is equal in magnitude and opposite in direction.

  $$\vec{F}_{A\ on\ B} = -\vec{F}_{B\ on\ A}$$

  $\vec{F}_{A\ on\ B}$ and $-\vec{F}_{B\ on\ A}$ are action - reaction pair

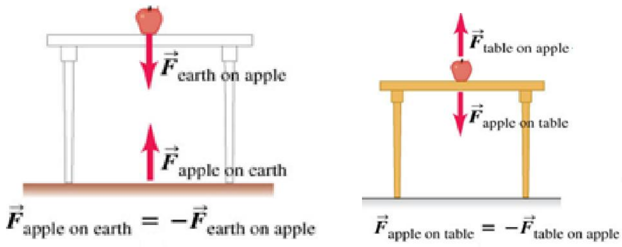
- When we drop a ball, both the ball and the earth accelerate toward each other. The net force on each body has the same magnitude, but the earth's acceleration is microscopically small because its mass is so great. Nevertheless it does move.

Q: An apple rests on a table. Identify the forces that act on it and the action-reaction pairs.

Ans: Action-reaction pairs are:

1. $\vec{F}_{\text{apple on earth}} = -\vec{F}_{\text{earth on apple}}$

2. $\vec{F}_{\text{apple on table}} = -\vec{F}_{\text{table on apple}}$



Test your Understanding (TYU): TYU-4.2, TYU-4.3, TYU-4.4

Test Your Understanding of Section 4.2

In which of the following situations is there zero net force on the body?

(i) an airplane flying due north at a steady 120 m/s and at a constant altitude;
(ii) a car driving straight up a hill with 3^0 a slope at a constant 90 km/h
(iii) a hawk circling at a constant 20 km/h at a constant height of 15 m above an open field;
(iv) a box with slick, frictionless surfaces in the back of a truck as the truck accelerates forward on a level road at 5 m/s^2.

Answer: (i), (ii), and (iv)

In (i), (ii), and (iv) the body is **not** accelerating, so the net force on the body is zero.
In (iv), the box remains stationary as seen in the inertial reference frame of the ground as the truck accelerates forward.
In (iii), the hawk is moving in a circle; hence it is accelerating and is not in equilibrium.

Test Your Understanding of Section 4.3

Rank the following situations in order of the magnitude of the object's acceleration, from lowest to highest. Are there any cases that have the same magnitude of acceleration?

(i) a 2.0-kg object acted on by a 2.0-N net force;
(ii) a 2.0-kg object acted on by an 8.0-N net force;
(iii) an 8.0-kg object acted on by a 2.0-N net force;
(iv) an 8.0-kg object acted on by a 8.0-N net force.

Answer: 1st - (iii), 2nd - (i) and (iv) (tie), 3rd - (ii)

The acceleration is equal to the net force divided by the mass. Hence the magnitude of the acceleration in each situation is

(i) $a = \dfrac{(2.0\text{N})}{(2.0\text{kg})} = 1.0 \text{ m/s}^2$ (ii) $a = \dfrac{(8.0\text{N})}{(2.0\text{kg})} = 4.0 \text{ m/s}^2$

(iii) $a = \dfrac{(2.0\text{N})}{(8.0\text{kg})} = 0.25 \text{ m/s}^2$ (iv) $a = \dfrac{(8.0\text{N})}{(8.0\text{kg})} = 1.0 \text{ m/s}^2$

Test Your Understanding of Section 4.4

Suppose an astronaut landed on a planet where g = 19.6 m/s^2. Compared to earth, would it be easier, harder, or just as easy for her to walk around? Would it be easier, harder, or just as easy for her to catch a ball that is moving horizontally at 12 m/s. (Assume that the astronaut's spacesuit is a lightweight model that doesn't impede her movements in any way)

Answer:

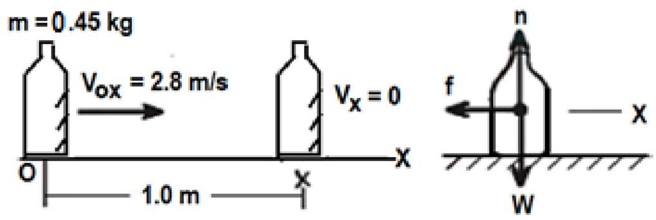
Weight of the astronaut in earth = mg ($g = 9.8$ m/s^2)
Weight of the astronaut in planet = mg' = m (2g) = 2mg, ($g' = 19.6$ m/s$^2 = 2g$)
Thus astronaut's weight on the planet would be twice as much as on the earth.

So, it would take twice the effort for the astronaut to walk around on the planet.
But it would be just as easy to catch a ball moving horizontally. The ball's mass is the same as on earth, so the horizontal force the astronaut would have to exert to bring it to a stop (i.e., to give it the same acceleration) would also be the same as on earth.

Example Problem: 4.5, 4.7

Example: 4.5

A waitress shoves (push roughly) a ketchup bottle with mass 0.45 kg to the right along a smooth, level lunch counter. The bottle leaves her hand moving at 2.8 m/s, and then slows down as it slides because of the constant horizontal friction force exerted on it by the counter top. It slides a distance of 1.0 m before coming to rest. What are the magnitude and direction of the friction force acting on the bottle?



Solution:

We know that

$$v_x^2 = v_{ox}^2 + 2\,a_x\left(x - x_0\right) \quad \Rightarrow \quad a_x = \frac{v_x^2 - v_{ox}^2}{2\left(x - x_0\right)}$$

$$\Rightarrow \quad a_x = \frac{\left(0\ \text{m/s}\right)^2 - \left(2.8\text{m/s}\right)^2}{2\left(1.0\ \text{m} - 0\ \text{m}\right)} = -3.9\ \text{m/s}^2$$

The negative sign means that the bottle's acceleration is opposite to its velocity; so the bottle is slowing down.

The net force in the *x*-direction is the frictional force. So,

$\sum F_x = f = ma_x = (0.45\ \text{kg})(-3.9\ \text{m/s}^2) = -1.8\ \text{N}$

The magnitude of the friction force is 1.8 N

Example: 4.7

A 2.49×10^4N Rolls-Royce Phantom travelling in the +x-direction makes an emergency stop; the x-component of the net force acting on it is -1.83×10^4N .What is its acceleration?

Mass of the car is

$$m = \frac{w}{g} \quad \Rightarrow \quad m = \frac{2.49 \text{ x } 10^4\text{N}}{9.8\text{m/s}^2} = 2540\text{kg}$$

Now,

$$\sum F_x = m\,a_x$$

$$a_x = \frac{\sum F_x}{m} = \frac{-1.83 \text{ x } 10^4\text{N}}{2540\text{kg}} = -7.2\text{m/s}^2$$