



Chapter 4 : Laws of Motion (Solved Examples & Exercises)

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Notes

Step-by-step solutions · NCERT Examples 4.1–4.12 and Exercises 4.1–4.23 · Class 11 Physics

Part A — NCERT Solved Examples

Example 4.1

Question: An astronaut accidentally gets separated out of his small spaceship accelerating in interstellar space at a constant rate of 100 m s^{-2} . What is the acceleration of the astronaut the instant after he is outside the spaceship? (Assume that there are no nearby stars to exert gravitational force on him.)

Solution: There are no nearby stars, and the small spaceship exerts a negligible gravitational attraction. Once the astronaut is out of the spaceship, **no external force acts on him**. By Newton's first law, his acceleration is zero.

Answer: Zero.

Example 4.2

Question: A bullet of mass 0.04 kg moving with a speed of 90 m s^{-1} enters a heavy wooden block and is stopped after a distance of 60 cm . What is the average resistive force exerted by the block on the bullet?

Solution: $u = 90 \text{ m s}^{-1}$, $v = 0$, $s = 0.60 \text{ m}$. Using $v^2 = u^2 + 2as$:

$$a = \frac{-u^2}{2s} = \frac{-(90)^2}{2 \times 0.6} = -6750 \text{ m s}^{-2}$$

$$F = ma = 0.04 \times 6750 = 270 \text{ N}$$

Answer: The average resistive force is **270 N**. (The actual force may not be uniform, so this is the average.)

Example 4.3

Question: The motion of a particle of mass m is described by $y = ut + \frac{1}{2}gt^2$. Find the force acting on the particle.

Solution:

$$v = \frac{dy}{dt} = u + gt, \quad a = \frac{dv}{dt} = g$$

$$F = ma = mg$$

Answer: $F = mg$. The equation describes a particle under acceleration due to gravity, and y is the position coordinate in the direction of g .

Example 4.4

Question: A batsman hits back a ball straight in the direction of the bowler without changing its initial speed of 12 m s^{-1} . If the mass of the ball is 0.15 kg , determine the impulse imparted to the ball. (Assume linear motion of the ball.)

Solution:

$$\text{Impulse} = \Delta p = 0.15 \times 12 - (-0.15 \times 12) = 3.6 \text{ N s}$$

Answer: **3.6 N s**, in the direction from the batsman to the bowler. (The force and the contact time are hard to know separately, but the impulse is easily found.)

Example 4.5

Question: Two identical billiard balls strike a rigid wall with the same speed but at different angles, and get reflected without any change in speed, as shown in Fig. 4.6. What is (i) the direction of the force on the wall due to each ball? (ii) the ratio of the magnitudes of impulses imparted to the balls by the wall?

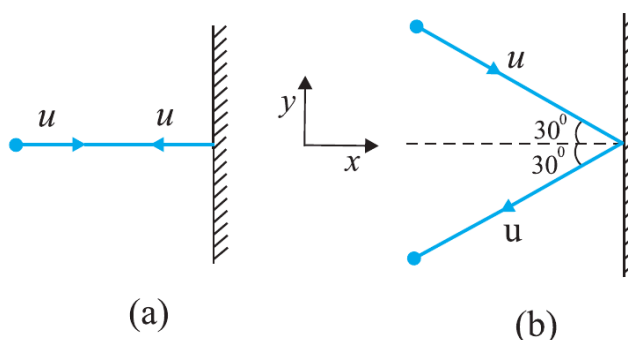


Fig. 4.6

Solution: Take the x-axis normal to the wall.

Case (a): $(p_x)_{\text{initial}} = mu$, $(p_x)_{\text{final}} = -mu$; $(p_y) = 0$. Impulse = $-2mu$ along x, 0 along y.

Case (b): $(p_x)_{\text{initial}} = mu \cos 30^\circ$, $(p_x)_{\text{final}} = -mu \cos 30^\circ$; $(p_y)_{\text{initial}} = 0$, $(p_y)_{\text{final}} = mu \sin 30^\circ$.

Impulse = $-2mu \cos 30^\circ$ along x, 0 along y.

(i) In both cases the force on the ball is along $-x$ (normal to the wall). By Newton's third law, the force on the wall is **normal to the wall, along $+x$** .

(ii)

$$\frac{\text{Impulse (a)}}{\text{Impulse (b)}} = \frac{2mu}{2mu \cos 30^\circ} = \frac{2}{\sqrt{3}} \approx 1.2$$

Answer: (i) Normal to the wall in both cases; (ii) $2/\sqrt{3} \approx 1.2$.

Example 4.6

Question: See Fig. 4.8. A mass of 6 kg is suspended by a rope of length 2 m from the ceiling. A force of 50 N in the horizontal direction is applied at the midpoint P of the rope, as shown. What is the angle the rope makes with the vertical in equilibrium? (Take $g = 10 \text{ m s}^{-2}$.) Neglect the mass of the rope.

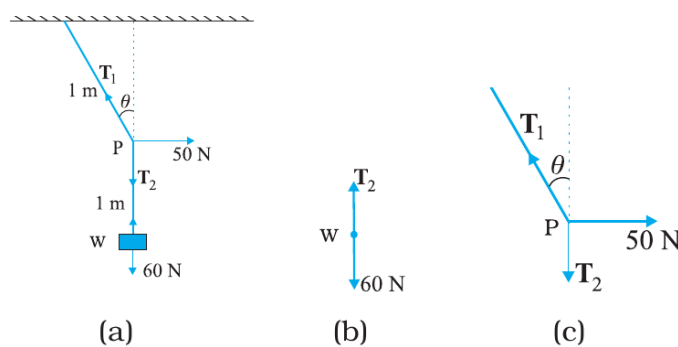


Fig. 4.8

Solution: For the weight W (Fig. 4.8(b)): $T_2 = 6 \times 10 = 60 \text{ N}$.

For point P (Fig. 4.8(c)), with T_1 making angle θ with the vertical:

$$T_1 \cos \theta = T_2 = 60 \text{ N}, \quad T_1 \sin \theta = 50 \text{ N}$$

$$\tan \theta = \frac{5}{6} \Rightarrow \theta = \tan^{-1} \left(\frac{5}{6} \right) = 40^\circ$$

Answer: $\theta \approx 40^\circ$. The answer does not depend on the length of the rope (massless) nor on the point at which the force is applied.

Example 4.7

Question: Determine the maximum acceleration of the train in which a box lying on its floor will remain stationary, given that the coefficient of static friction between the box and the train's floor is 0.15.

Solution: The acceleration of the box is due only to static friction:

$$ma = f_s \leq \mu_s N = \mu_s mg \Rightarrow a \leq \mu_s g$$

$$a_{\max} = \mu_s g = 0.15 \times 10 = 1.5 \text{ m s}^{-2}$$

Answer: 1.5 m s^{-2} .

Example 4.8

Question: See Fig. 4.11. A mass of 4 kg rests on a horizontal plane. The plane is gradually inclined until at an angle $\theta = 15^\circ$ with the horizontal, the mass just begins to slide. What is the coefficient of static friction between the block and the surface?

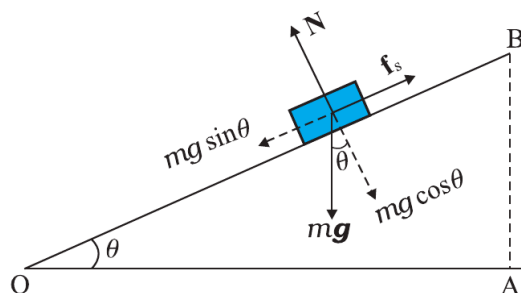


Fig. 4.11

Solution: In equilibrium: $mg \sin \theta = f_s$ and $mg \cos \theta = N$. When the block is about to slide, $f_s = (f_s)_{\max} = \mu_s N$:

$$\mu_s = \tan \theta_{\max} = \tan 15^\circ = 0.27$$

Answer: $\mu_s = 0.27$. (It does not depend on the mass of the block.)

Example 4.9

Question: What is the acceleration of the block and trolley system shown in Fig. 4.12(a), if the coefficient of kinetic friction between the trolley and the surface is 0.04? What is the tension in the string? (Take $g = 10 \text{ m s}^{-2}$.) Neglect the mass of the string.

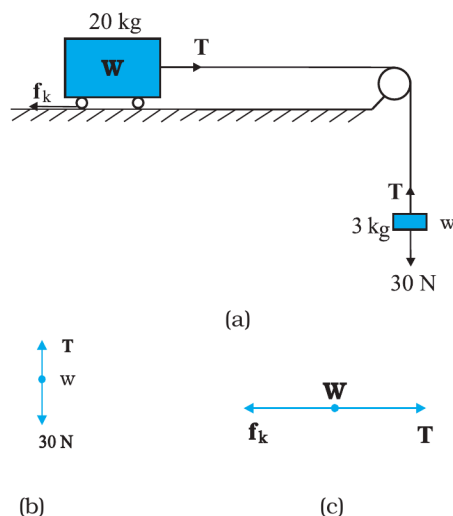


Fig. 4.12

Solution: Block (3 kg), Fig. 4.12(b):

$$30 - T = 3a$$

Trolley (20 kg), Fig. 4.12(c): $f_k = \mu_k N = 0.04 \times 20 \times 10 = 8 \text{ N}$.

$$T - 8 = 20a$$

Adding: $22 = 23a \Rightarrow a = 0.96 \text{ m s}^{-2}$. Then $T = 30 - 3(0.96) = 27.1 \text{ N}$.

Answer: $a = 0.96 \text{ m s}^{-2}$; $T = 27.1 \text{ N}$.

Example 4.10

Question: A cyclist speeding at 18 km/h on a level road takes a sharp circular turn of radius 3 m without reducing the speed. The coefficient of static friction between the tyres and the road is 0.1. Will the cyclist slip while taking the turn?

Solution: On an unbanked road, friction alone provides the centripetal force. The condition for not slipping is $v^2 \leq \mu_s Rg$.

$v = 18 \text{ km/h} = 5 \text{ m s}^{-1}$, so $v^2 = 25 \text{ m}^2 \text{ s}^{-2}$.

$$\mu_s Rg = 0.1 \times 3 \times 9.8 = 2.94 \text{ m}^2 \text{ s}^{-2}$$

Answer: Since $v^2 > \mu_s Rg$, the cyclist will slip while taking the turn.

Example 4.11

Question: A circular racetrack of radius 300 m is banked at an angle of 15° . If the coefficient of friction between the wheels of a race-car and the road is 0.2, what is the (a) optimum speed of the race-car to avoid wear and tear on its tyres, and (b) maximum permissible speed to avoid slipping?

Solution: On a banked road, the horizontal component of the normal force and the frictional force provide the centripetal force.

(a) Optimum speed (no friction needed):

$$v_o = (Rg \tan \theta)^{1/2} = (300 \times 9.8 \times \tan 15^\circ)^{1/2} = 28.1 \text{ m s}^{-1}$$

(b) Maximum permissible speed:

$$v_{max} = \left(Rg \frac{\mu_s + \tan \theta}{1 - \mu_s \tan \theta} \right)^{1/2} = \left(300 \times 9.8 \times \frac{0.2 + 0.268}{1 - 0.2 \times 0.268} \right)^{1/2} = 38.1 \text{ m s}^{-1}$$

Answer: (a) 28.1 m s^{-1} ; (b) 38.1 m s^{-1} .

Example 4.12

Question: See Fig. 4.15. A wooden block of mass 2 kg rests on a soft horizontal floor. When an iron cylinder of mass 25 kg is placed on top of the block, the floor yields steadily and the block and the cylinder together go down with an acceleration of 0.1 m s^{-2} . What is the action of the block on the floor (a) before and (b) after the floor yields? Take $g = 10 \text{ m s}^{-2}$. Identify the action-reaction pairs in the problem.

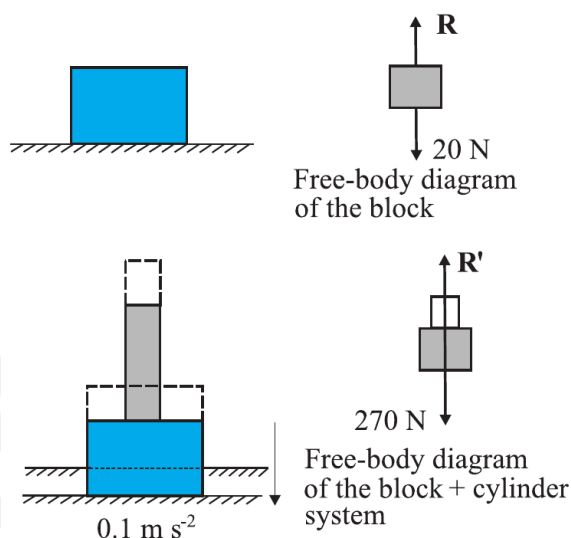


Fig. 4.15

Solution:

(a) The block is at rest on the floor. Its free-body diagram shows two forces: gravity $2 \times 10 = 20 \text{ N}$ downward and the normal force R of the floor upward. By the first law, $R = 20 \text{ N}$. By the third law, **the action of the block on the floor is 20 N, directed vertically downwards.**

(b) Take the system (block + cylinder). It accelerates downward at 0.1 m s^{-2} . Forces: weight $(2 + 25) \times 10 = 270 \text{ N}$ downward; normal force R' upward:

$$270 - R' = 27 \times 0.1 \quad \Rightarrow \quad R' = 267.3 \text{ N}$$

By the third law, **the action of the system on the floor is 267.3 N, vertically downward.**

Action-reaction pairs:

- a. Force of gravity on the block by the earth (20 N down) and the force of gravity on the earth by the block (20 N up, not shown). Force on the floor by the block (20 N down) and force on the block by the floor (20 N up).
- b. Force of gravity on the system by the earth (270 N down) and on the earth by the system (270 N up). Force on the floor by the system (267.3 N down) and on the system by the floor (267.3 N up). Also, force on the block by the cylinder and on the cylinder by the block.

Note: The weight (270 N) and the normal force R' (267.3 N) are **not** an action-reaction pair. They are not equal here because the system is accelerating.

Part B — NCERT Exercises

(For simplicity in numerical calculations, take $g = 10 \text{ m s}^{-2}$.)

Exercise 4.1

Question: Give the magnitude and direction of the net force acting on (a) a drop of rain falling down with a constant speed, (b) a cork of mass 10 g floating on water, (c) a kite skilfully held stationary in the sky, (d) a car moving with a constant velocity of 30 km/h on a rough road, (e) a high-speed electron in space far from all material objects, and free of electric and magnetic fields.

Answer: In all five cases the body has **zero acceleration** (constant velocity or at rest). By Newton's first law, the **net force is zero** in each case:

- a. Weight is balanced by air resistance and buoyancy.
- b. Weight is balanced by the buoyant force.
- c. Forces on the kite (wind, weight, string tension) balance.
- d. The driving force is balanced by friction.
- e. No force acts on the electron.

Exercise 4.2

Question: A pebble of mass 0.05 kg is thrown vertically upwards. Give the direction and magnitude of the net force on the pebble, (a) during its upward motion, (b) during its downward motion, (c) at the highest point where it is momentarily at rest. Do your answers change if the pebble was thrown at an angle of 45° with the horizontal direction? Ignore air resistance.

Answer: The only force acting is gravity (air resistance neglected):

$$F = mg = 0.05 \times 10 = 0.5 \text{ N, vertically downward}$$

in **all three cases** (a), (b) and (c). Even at the highest point ($v = 0$), the force is mg .

No, the answers do not change for a pebble thrown at 45° . The net force is still 0.5 N downward at every point of its path. (At the highest point, the pebble now has a horizontal velocity, but the force is unchanged.)

Exercise 4.3

Question: Give the magnitude and direction of the net force acting on a stone of mass 0.1 kg, (a) just after it is dropped from the window of a stationary train, (b) just after it is dropped from the window of a train running at a constant velocity of 36 km/h, (c) just after it is dropped from the window of a train accelerating with 1 m s^{-2} , (d) lying on the floor of a train which is accelerating with 1 m s^{-2} , the stone being at rest relative to the train. Neglect air resistance throughout.

Solution:

- (a) $F = mg = 0.1 \times 10 = 1 \text{ N}$, vertically downward.
- (b) Same: **1 N, vertically downward**. The train's constant velocity adds no force.
- (c) Same: **1 N, vertically downward**. Once released, the stone is no longer accelerated by the train (force is a local relation; it carries no memory of the train's acceleration).
- (d) The stone accelerates with the train at 1 m s^{-2} . Its weight is balanced by the normal reaction. The net force is horizontal: $F = ma = 0.1 \times 1 = 0.1 \text{ N}$, **along the direction of motion of the train**.

Exercise 4.4

Question: One end of a string of length l is connected to a particle of mass m and the other to a small peg on a smooth horizontal table. If the particle moves in a circle with speed v , the net force on the particle (directed towards the centre) is: (i) T , (ii) $T - \frac{mv^2}{l}$, (iii) $T + \frac{mv^2}{l}$, (iv) 0 . T is the tension in the string. [Choose the correct alternative.]

Answer: (i) T . The table is smooth and horizontal, so weight and normal force cancel. The only horizontal force is the tension T , which provides the centripetal force: $T = \frac{mv^2}{l}$.

Exercise 4.5

Question: A constant retarding force of 50 N is applied to a body of mass 20 kg moving initially with a speed of 15 m s^{-1} . How long does the body take to stop?

Solution:

$$a = \frac{-F}{m} = \frac{-50}{20} = -2.5\text{ m s}^{-2}$$

$$v = u + at \Rightarrow 0 = 15 - 2.5t \Rightarrow t = 6\text{ s}$$

Answer: 6 s .

Exercise 4.6

Question: A constant force acting on a body of mass 3.0 kg changes its speed from 2.0 m s^{-1} to 3.5 m s^{-1} in 25 s . The direction of the motion of the body remains unchanged. What is the magnitude and direction of the force?

Solution:

$$a = \frac{v - u}{t} = \frac{3.5 - 2.0}{25} = 0.06\text{ m s}^{-2}, \quad F = ma = 3.0 \times 0.06 = 0.18\text{ N}$$

Answer: 0.18 N , along the direction of motion of the body.

Exercise 4.7

Question: A body of mass 5 kg is acted upon by two perpendicular forces 8 N and 6 N . Give the magnitude and direction of the acceleration of the body.

Solution:

$$F = \sqrt{8^2 + 6^2} = 10\text{ N}, \quad a = \frac{F}{m} = \frac{10}{5} = 2\text{ m s}^{-2}$$

Direction (angle with the 8 N force):

$$\tan \theta = \frac{6}{8} \Rightarrow \theta = 36.87^\circ$$

Answer: 2 m s^{-2} , at about 37° with the 8 N force (along the resultant force).

Exercise 4.8

Question: The driver of a three-wheeler moving with a speed of 36 km/h sees a child standing in the middle of the road and brings his vehicle to rest in 4.0 s just in time to save the child. What is the average retarding force on the vehicle? The mass of the three-wheeler is 400 kg and the mass of the driver is 65 kg .

Solution: $u = 36\text{ km/h} = 10\text{ m s}^{-1}$, $v = 0$, $t = 4\text{ s}$. Total mass = 465 kg .

$$a = \frac{0 - 10}{4} = -2.5 \text{ m s}^{-2}, \quad F = 465 \times 2.5 = 1162.5 \text{ N}$$

Answer: Average retarding force $\approx 1.16 \times 10^3 \text{ N}$, opposite to the direction of motion.

Exercise 4.9

Question: A rocket with a lift-off mass 20,000 kg is blasted upwards with an initial acceleration of 5.0 m s^{-2} . Calculate the initial thrust (force) of the blast.

Solution: The thrust F acts upward and weight mg acts downward:

$$F - mg = ma \Rightarrow F = m(g + a) = 20000 \times (10 + 5) = 3.0 \times 10^5 \text{ N}$$

Answer: $3.0 \times 10^5 \text{ N}$, vertically upward.

Exercise 4.10

Question: A body of mass 0.40 kg moving initially with a constant speed of 10 m s^{-1} to the north is subject to a constant force of 8.0 N directed towards the south for 30 s. Take the instant the force is applied to be $t = 0$, the position of the body at that time to be $x = 0$, and predict its position at $t = -5 \text{ s}$, 25 s, 100 s.

Solution: Take north as positive. $a = \frac{-8.0}{0.40} = -20 \text{ m s}^{-2}$, acting only from $t = 0$ to $t = 30 \text{ s}$.

- **$t = -5 \text{ s}$:** no force before $t = 0$, uniform motion: $x = 10 \times (-5) = -50 \text{ m}$.
- **$t = 25 \text{ s}$:** $x = ut + \frac{1}{2}at^2 = 10(25) + \frac{1}{2}(-20)(25)^2 = 250 - 6250 = -6000 \text{ m} = -6 \text{ km}$.
- **$t = 100 \text{ s}$:** First find the motion up to 30 s:

$$x(30) = 10(30) - 10(30)^2 = -8700 \text{ m}, \quad v(30) = 10 - 20 \times 30 = -590 \text{ m s}^{-1}$$

After 30 s the force stops, so the body moves uniformly for 70 s more:

$$x(100) = -8700 + (-590)(70) = -50000 \text{ m} = -50 \text{ km}$$

Answer: -50 m, -6 km and -50 km (negative means south of the starting point).

Exercise 4.11

Question: A truck starts from rest and accelerates uniformly at 2.0 m s^{-2} . At $t = 10 \text{ s}$, a stone is dropped by a person standing on the top of the truck (6 m high from the ground). What are the (a) velocity, and (b) acceleration of the stone at $t = 11 \text{ s}$? (Neglect air resistance.)

Solution: At $t = 10 \text{ s}$, the truck's speed $= 2 \times 10 = 20 \text{ m s}^{-1}$. The stone keeps this horizontal velocity after release (no horizontal force).

(a) At $t = 11 \text{ s}$ (1 s after release): $v_x = 20 \text{ m s}^{-1}$, $v_y = 10 \times 1 = 10 \text{ m s}^{-1}$ downward. (In 1 s it falls 5 m $<$ 6 m, so it is still in the air.)

$$v = \sqrt{20^2 + 10^2} = 22.4 \text{ m s}^{-1}, \quad \tan \theta = \frac{10}{20} \Rightarrow \theta = 26.6^\circ \text{ below the horizontal}$$

(b) Once dropped, the only force is gravity: **$a = 10 \text{ m s}^{-2}$, vertically downward.**

Exercise 4.12

Question: A bob of mass 0.1 kg hung from the ceiling of a room by a string 2 m long is set into oscillation. The speed of the bob at its mean position is 1 m s^{-1} . What is the trajectory of the bob if the string is cut when the bob is (a) at one of its extreme positions, (b) at its mean position?

Answer:

- (a) At an extreme position, the bob is momentarily at rest. When the string is cut, it **falls vertically downward** (free fall).
- (b) At the mean position, the bob has a horizontal velocity of 1 m s^{-1} . When the string is cut, it follows a **parabolic path** (like a horizontally projected body).

Exercise 4.13

Question: A man of mass 70 kg stands on a weighing scale in a lift which is moving (a) upwards with a uniform speed of 10 m s^{-1} , (b) downwards with a uniform acceleration of 5 m s^{-2} , (c) upwards with a uniform acceleration of 5 m s^{-2} . What would be the readings on the scale in each case? (d) What would be the reading if the lift mechanism failed and it hurtled down freely under gravity?

Solution: The scale reads the normal force R .

- (a) Uniform speed ($a = 0$): $R = mg = 70 \times 10 = 700 \text{ N} \rightarrow \mathbf{70 \text{ kg}}$.
- (b) Downward acceleration: $R = m(g - a) = 70 \times 5 = 350 \text{ N} \rightarrow \mathbf{35 \text{ kg}}$.
- (c) Upward acceleration: $R = m(g + a) = 70 \times 15 = 1050 \text{ N} \rightarrow \mathbf{105 \text{ kg}}$.
- (d) Free fall ($a = g$): $R = m(g - g) = 0 \rightarrow \mathbf{\text{zero}}$ (weightlessness).

Exercise 4.14

Question: Figure 4.16 shows the position-time graph of a particle of mass 4 kg . What is the (a) force on the particle for $t < 0$, $t > 4 \text{ s}$, $0 < t < 4 \text{ s}$? (b) impulse at $t = 0$ and $t = 4 \text{ s}$? (Consider one-dimensional motion only.)

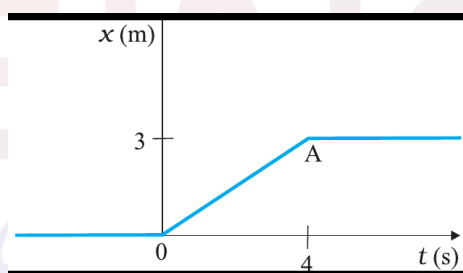


Fig. 4.16

Solution:

(a) In each interval the x - t graph is a straight line, so the velocity is constant and the acceleration is zero. **The force is zero** for $t < 0$, $0 < t < 4 \text{ s}$, and $t > 4 \text{ s}$.

(b) Velocity: $t < 0 \rightarrow 0$; $0 < t < 4 \text{ s} \rightarrow v = 3/4 = 0.75 \text{ m s}^{-1}$; $t > 4 \text{ s} \rightarrow 0$.

- At $t = 0$: Impulse $= m(v - u) = 4(0.75 - 0) = +3 \text{ kg m s}^{-1}$.
- At $t = 4 \text{ s}$: Impulse $= 4(0 - 0.75) = -3 \text{ kg m s}^{-1}$.

Answer: (a) zero in all intervals; (b) $+3 \text{ kg m s}^{-1}$ at $t = 0$ and -3 kg m s^{-1} at $t = 4 \text{ s}$.

Exercise 4.15

Question: Two bodies of masses 10 kg and 20 kg respectively kept on a smooth, horizontal surface are tied to the ends of a light string. A horizontal force $F = 600 \text{ N}$ is applied to (i) A, (ii) B along the direction of the string. What is the tension in the string in each case?

Solution: Common acceleration:

$$a = \frac{F}{m_A + m_B} = \frac{600}{30} = 20 \text{ m s}^{-2}$$

(i) **Force on A (10 kg):** the string drags B (20 kg): $T = m_B a = 20 \times 20 = 400 \text{ N}$.

(ii) **Force on B (20 kg):** the string drags A (10 kg): $T = m_A a = 10 \times 20 = 200 \text{ N}$.

Answer: (i) 400 N; (ii) 200 N.

Exercise 4.16

Question: Two masses 8 kg and 12 kg are connected at the two ends of a light inextensible string that goes over a frictionless pulley. Find the acceleration of the masses, and the tension in the string when the masses are released.

Solution: The 12 kg mass moves down and the 8 kg mass moves up:

$$a = \frac{(m_1 - m_2)g}{m_1 + m_2} = \frac{(12 - 8) \times 10}{20} = 2 \text{ m s}^{-2}$$

$$T = \frac{2m_1 m_2 g}{m_1 + m_2} = \frac{2 \times 12 \times 8 \times 10}{20} = 96 \text{ N}$$

(Check: for 8 kg, $T - 80 = 8 \times 2 \Rightarrow T = 96 \text{ N} \checkmark$.)

Answer: $a = 2 \text{ m s}^{-2}$; $T = 96 \text{ N}$.

Exercise 4.17

Question: A nucleus is at rest in the laboratory frame of reference. Show that if it disintegrates into two smaller nuclei the products must move in opposite directions.

Solution: Initial momentum = 0 (nucleus at rest). The disintegration is caused by internal forces only, so momentum is conserved:

$$0 = m_1 \vec{v}_1 + m_2 \vec{v}_2 \Rightarrow \vec{v}_1 = -\frac{m_2}{m_1} \vec{v}_2$$

Answer: The negative sign shows that $\vec{v}_1$ and $\vec{v}_2$ are in **opposite directions** (and along the same line).

Exercise 4.18

Question: Two billiard balls each of mass 0.05 kg moving in opposite directions with speed 6 m s^{-1} collide and rebound with the same speed. What is the impulse imparted to each ball due to the other?

Solution: For one ball: initial momentum = $0.05 \times 6 = 0.3 \text{ kg m s}^{-1}$; final momentum = -0.3 kg m s^{-1} .

$$\text{Impulse} = \Delta p = -0.3 - 0.3 = -0.6 \text{ kg m s}^{-1}$$

Answer: 0.6 kg m s^{-1} for each ball, directed opposite to its initial motion. (The two impulses are equal and opposite.)

Exercise 4.19

Question: A shell of mass 0.020 kg is fired by a gun of mass 100 kg. If the muzzle speed of the shell is 80 m s^{-1} , what is the recoil speed of the gun?

Solution: By conservation of momentum (initially at rest):

$$m_g v_g = m_s v_s \Rightarrow v_g = \frac{0.020 \times 80}{100} = 0.016 \text{ m s}^{-1}$$

Answer: 0.016 m s^{-1} ($= 1.6 \text{ cm s}^{-1}$), opposite to the shell.

Exercise 4.20

Question: A batsman deflects a ball by an angle of 45° without changing its initial speed which is equal to 54 km/h. What is the impulse imparted to the ball? (Mass of the ball is 0.15 kg.)

Solution: $v = 54 \text{ km/h} = 15 \text{ m s}^{-1}$. Take the x-axis along the line that bisects the angle between the incoming and outgoing directions of the ball (the line normal to the bat's face). The ball's incoming and outgoing velocities each make an angle of 22.5° with this line. The component of velocity along x reverses ($v \cos 22.5^\circ \rightarrow -v \cos 22.5^\circ$), while the perpendicular component $v \sin 22.5^\circ$ is unchanged:

$$\text{Impulse} = 2mv \cos 22.5^\circ = 2 \times 0.15 \times 15 \times 0.924 = 4.16 \text{ kg m s}^{-1}$$

Answer: About 4.2 kg m s^{-1} , along the bisector of the angle between the incoming and outgoing paths.

Exercise 4.21

Question: A stone of mass 0.25 kg tied to the end of a string is whirled round in a circle of radius 1.5 m with a speed of 40 rev/min in a horizontal plane. What is the tension in the string? What is the maximum speed with which the stone can be whirled around if the string can withstand a maximum tension of 200 N ?

Solution: $\omega = 2\pi \times \frac{40}{60} = 4.19 \text{ rad s}^{-1}$.

$$T = m\omega^2 r = 0.25 \times (4.19)^2 \times 1.5 = 6.6 \text{ N}$$

Maximum speed: $T_{\max} = \frac{mv_{\max}^2}{r}$:

$$v_{\max} = \sqrt{\frac{T_{\max} r}{m}} = \sqrt{\frac{200 \times 1.5}{0.25}} = \sqrt{1200} = 34.6 \text{ m s}^{-1}$$

Answer: $T \approx 6.6 \text{ N}$; $v_{\max} \approx 34.6 \text{ m s}^{-1}$.

Exercise 4.22

Question: If, in Exercise 4.21, the speed of the stone is increased beyond the maximum permissible value, and the string breaks suddenly, which of the following correctly describes the trajectory of the stone after the string breaks: (a) the stone moves radially outwards, (b) the stone flies off tangentially from the instant the string breaks, (c) the stone flies off at an angle with the tangent whose magnitude depends on the speed of the particle?

Answer: (b). At every instant, the velocity of the stone is along the tangent. When the string breaks, the centripetal force vanishes, and by the first law the stone continues in a straight line **along the tangent** at that point.

Exercise 4.23

Question: Explain why (a) a horse cannot pull a cart and run in empty space, (b) passengers are thrown forward from their seats when a speeding bus stops suddenly, (c) it is easier to pull a lawn mower than to push it, (d) a cricketer moves his hands backwards while holding a catch.

Answer:

- **(a)** To run, the horse pushes the ground backward; by the third law, the ground pushes the horse forward. In empty space there is no ground (no external body) to push against, so no forward reaction force acts.
- **(b)** When the bus stops, the passengers' feet stop with it (due to friction), but the upper body continues moving forward due to **inertia of motion**.
- **(c) Pulling** at angle θ above the horizontal: the vertical component $F \sin \theta$ acts upward, reducing the normal force to $mg - F \sin \theta$, so friction is smaller. **Pushing** downward at angle θ increases the normal force to $mg + F \sin \theta$, so friction is larger.
- **(d)** Moving the hands back **increases the time** taken to stop the ball. Since $F = \Delta p / \Delta t$, a longer time means a **smaller force** on the hands, so they are not hurt.