4 Dynamics

Study Station ▸▸

A Newton's Laws of Motion

Learning Outcomes

- Use Newton's Laws of Motion to:
  (i) describe how balanced and unbalanced forces affect a body.
  (ii) describe how a force may change the motion of a body.
  (iii) identify the pair of action–reaction forces acting on two interacting bodies.
- Recall and apply the relationship *net force* = *mass* × *acceleration* to real-world situations and solve related problems.
- Understand that mass is the property of a body which resists the change in motion (inertia).

1. Newton's Laws of Motion is a set of *three rules regarding how motion relates to forces.*
2. In football, the motion of the ball follows the three Newton's Laws of Motion.

The table shows which Newton's Laws of Motion some physical actions follow.

Physical Action and Observation	Newton's Law of Motion
A stationary ball remains stationary unless it is kicked.	Newton's First Law of Motion
A ball tends to move straight with the same speed (i.e. velocity).	Newton's First Law of Motion
A ball that is kicked harder will move faster.	Newton's Second Law of Motion
The harder a player kicks a ball, the bigger the impact felt by the player's foot.	Newton's Third Law of Motion

10. Forces can cause acceleration (object moves faster) or deceleration (object moves slower). For example, when a bus driver wants the bus to stop, he steps on the brake (applies a decelerating force). When he wants the bus to move again, he steps on the accelerator (applies an accelerating force).

Worked Example 4.2

A mechanical engineer wants to design a motorcycle of mass 300 kg that can accelerate from 3 m/s to 25 m/s in a time of 5 s.

Calculate the forward force that needs to be supplied by the motorcycle engine.

Strategy

Recall acceleration = $\frac{\text{final velocity} - \text{initial velocity}}{\text{time taken}}$

Solution

Mass m = 300 kg

Initial velocity u = 3 m/s

Final velocity v = 25 m/s

Time taken t = 5 s

Acceleration $a = \frac{v-u}{t}$

$= \frac{25\text{ m/s} - 3\text{ m/s}}{5\text{ s}} = 4.4\text{ m/s}^2$

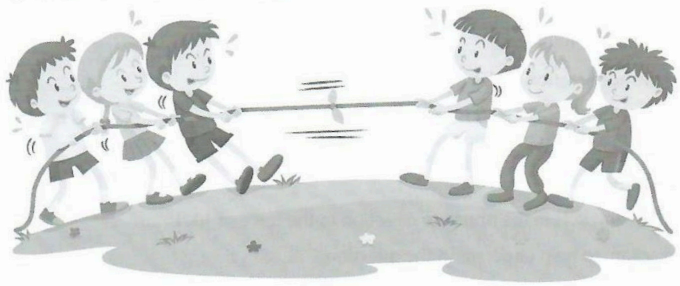
Using Newton's Second Law, $F_N = ma$

$= 300\text{ kg} \times 4.4\text{ m/s}^2 = 1320\text{ N}$

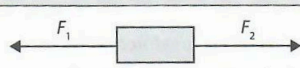
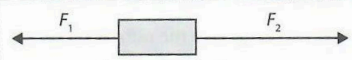
Tip

For horizontal motion, we can consider only the horizontal forces and ignore vertical forces such as weight.

11. If there are two forces acting on an object, we need to compare the magnitude and direction of the two forces. In the following example, if the people on the left pull harder than the people on the right, the rope will move to the left.



12. If there is more than one force acting on an object, we need to *add all the forces acting on the object to obtain the net force* F_N. Since force is a vector quantity, we need to consider their directions when adding them together. The table lists details about balanced and unbalanced forces.

Balanced Forces	Unbalanced Forces
 F_1 and F_2 are equal in magnitude but opposite in direction.	 F_2 is greater than F_1.
Net force, F_N is 0 (i.e. **balanced forces**)	Net force, $F_N \neq 0$ (i.e. **unbalanced forces**)
Acceleration, $a = 0$	Acceleration, $a \neq 0$ (direction of acceleration is the same as direction of net force)
Velocity remains the same	Velocity changes (according to acceleration)

Tip

Net force is not a type of force like weight or friction. It is just the total (or net) calculated using mathematics. For comparison, the total mass of two persons of mass 40 kg and 50 kg is 90 kg. Total mass of 90 kg does not mean it is the mass of any one person.

Worked Example 4.3

When a block of wood is pushed along a rough horizontal surface with a force of 10 N, the friction experienced is 4 N.

(a) Determine the net force.

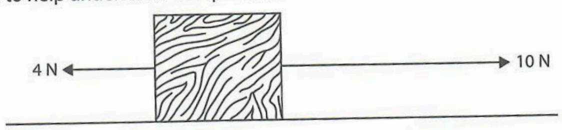
(b) Find the acceleration of the block of wood if its mass is 3 kg.

(c) When a larger force of 20 N is applied to the block of wood, a friction of 8 N is experienced. Find out the new acceleration.

Strategy

Note that friction acts in the opposite direction to the force of 10 N.

Draw a diagram to help understand the question.



Solution

(a) The force to the right is larger than the force to the left, so net force is to the right.

Net force $F_N = 10\text{ N} - 4\text{ N}$
$= 6\text{ N}$

(b) Using $F_N = ma$

$a = \frac{F_N}{m}$

$= \frac{6\text{ N}}{3\text{ kg}}$

$= 2\text{ m/s}^2$

(c) New net force $F_N = 20\text{ N} - 8\text{ N}$
$= 12\text{ N}$

Using $F_N = ma$

$a = \frac{F_N}{m}$

$= \frac{12\text{ N}}{3\text{ kg}}$

$= 4\text{ m/s}^2$

Explanation

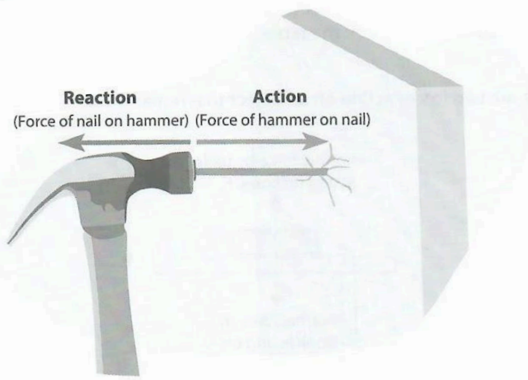
When net force increases, acceleration also increases.

13. **Newton's Third Law of Motion** states that *if an object **A** exerts a force on an object **B**, object **B** will exert a force which is the same in magnitude but opposite in direction on object **A**.*

14. Put more simply, according to Newton's Third Law of Motion,
    - *for every action, there is an equal and opposite reaction;*
    - *forces exist in pairs;*
    - *the pair of forces act on different objects.*

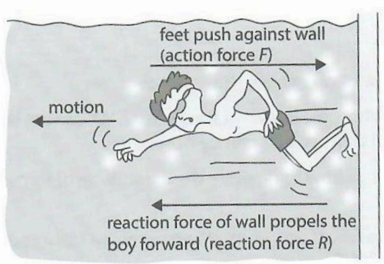
15. In other words, when object **A** pushes object **B**, object **B** will also push object **A** with the same magnitude of force but in the opposite direction.

    (a) When you use a hammer to hit a nail, the nail exerts a force in reaction to stop the hammer from moving.



Newton's Third Law

    (b) When you swim and push against the wall of the swimming pool, the wall pushes you so that you can move forward.



Newton's Third Law

Tip

An action–reaction pair must be of the same type of force. For example, if the action is a gravitational force (Earth pulls an object), the reaction must also be gravitational force (the object pulls Earth).

Worked Example 4.4

A book is lying stationary on a horizontal table. The two forces acting on the book are its weight and normal force.

(a) Are the forces balanced or unbalanced? Compare their magnitudes.

(b) Identify the action–reaction pair of forces in this situation.

Solution

(a) Balanced. Both have the same magnitude.

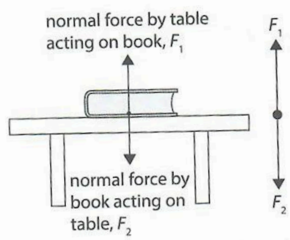
(b) The book's weight is the gravitational force exerted on it by the Earth. Thus, the corresponding reaction is the gravitational force exerted by it on the Earth.

The normal force is exerted on the book by the table. Thus, the corresponding reaction is the normal force exerted by the book on the table.

Explanation

(a) When there are two forces acting on an object that remains stationary, the forces must be balanced.

(b)



F_1 and F_2 are equal in magnitude but opposite in direction due to Newton's Third Law.

Link Discover Physics (5th Edition) Textbook — Section 4.1

Tip

The three Newton's Laws of Motion explain the concept of force.

- Newton's First Law tells us how we know if a force exists. We cannot see the force directly but we can deduce that it exists if its effects can be observed.
- Newton's Second Law tells us how to quantify the magnitude of forces and determine their directions.
- Newton's Third Law tells us forces always exist in pairs and a force can only appear due to interactions between two bodies.

Checkpoint 4.1

1. A student says that because the action–reaction pair of forces have the same magnitude but are opposite in directions, the net force is always zero. Explain the error in this understanding.

B Forces in Free-body Diagrams

Learning Outcomes

- Identify the forces acting on a body and draw the corresponding free-body diagram to represent the forces for cases involving forces acting in:
  - N (i) one dimension, and
  - O (ii) two dimensions.

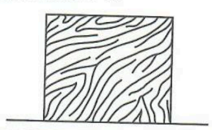
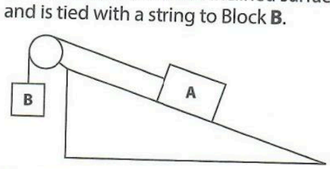
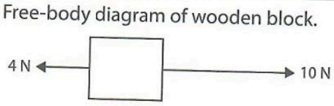
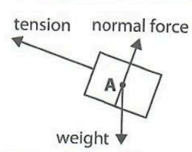
1. We draw a **free-body diagram** to help us *visually understand the forces acting on a body.*
   - Only *forces acting on that body are considered.*
   - *Forces exerted by the body are not considered.*
   - *Forces acting on other bodies are also not considered.*
   - The forces are *represented by arrows*. The directions of the arrows must indicate the directions of the forces. The lengths of the arrows do not necessarily represent the magnitudes of the forces unless they are drawn to scale.

N 2. Directions in one dimension can be:
   - left and right
   - up and down
   - forwards and backwards

N 3. For cases involving forces acting in *one dimension*, the forces are *either in the same direction or in opposite directions.*

O 4. For cases involving forces acting in *two dimensions*, the forces can be *in different directions in the same plane.*

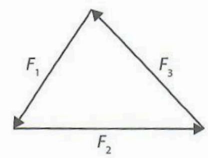
5. The table shows some examples of forces that act in N one dimension and those that act in O two dimensions.

<table>
<tr><th></th><th>N Forces That Act in One Dimension</th><th>O Forces That Act in Two Dimensions</th></tr>
<tr><td>Example</td><td>A wooden block is pushed to the right with a force of 10 N and experiences a frictional force of 4 N.
</td><td>Block A lies on a smooth inclined surface and is tied with a string to Block B.

</td></tr>
<tr><td>Free-body Diagram</td><td>Free-body diagram of wooden block.

</td><td>Free-body diagram of Block A.

</td></tr>
</table>

Tip

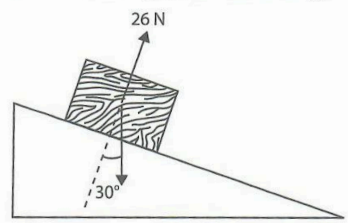
It is not necessary to show the net force in the free-body diagram.

6. If a body is *stationary*, the net force (sum of forces) that act on it is zero. If there are three forces, the *vector addition diagram* (using the head-to-tail vector addition method) must form a **closed triangle**.



Worked Example 4.5

A block of wood with mass 3 kg remains at rest on an inclined surface as shown in the diagram. The normal force acting on the block is 26 N. (Take *g* to be 10 N/kg)



(a) State the net force acting on the block.

(b) Calculate the weight of the block.

(c) Determine the direction of friction acting on the block.

(d) Determine the magnitude of friction acting on the block.

Strategy

(a) Note that a stationary object has zero acceleration and therefore the net force is zero.

(b) Recall weight, $W = mg$.

(c) Note that the combination of normal force and weight causes the block to tend to move downwards along the inclined surface.

(d) We need to draw a free-body diagram to understand the situation.

Solution

(a) 0 N

(b) Weight, $W = mg$

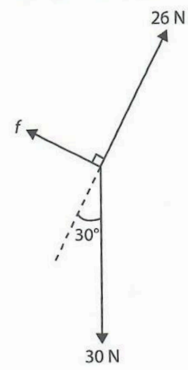
$= 3\text{ kg} \times 10\text{ N/kg}$

$= 30\text{ N}$

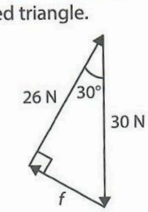
(c) The block tends to move downwards along the inclined surface. Since the block is stationary (remains at rest), the direction of friction must be in the opposite direction. Thus, direction of friction acting on the block is upwards along the inclined surface.

(d) Let f represent the friction acting on the block.

We can assume that the forces are acting on a single point to simplify the free-body diagram.



As the object is stationary, we know that the net force is zero. Thus, we can draw a vector addition diagram that forms a closed triangle.



Using Pythagoras' Theorem,

$a^2 + b^2 = c^2$

$f^2 + 26^2 = 30^2$

$f^2 = 30^2 - 26^2$

$= 224$

$f = 14.97$ N

$= 15$ N (2 sig. fig.)

Thus, friction is 15 N.

Explanation

Friction f can also be calculated graphically by drawing the closed triangle to scale and measuring directly from the diagram.

Link Discover Physics (5th Edition) Textbook — Section 4.2

Checkpoint 4.2

1. In Worked Example 4.5, why is the normal force acting on the inclined plane not shown in the force diagram?

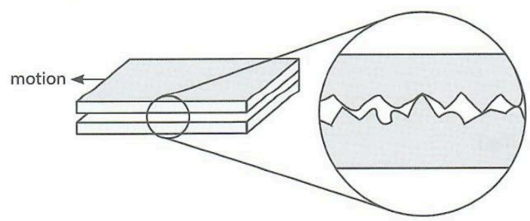
C Friction

Learning Outcome

- Explain how friction affects the motion of a body.

1. Friction is a force that *opposes motion* or the tendency of motion.
2. When we walk on a normal dry floor, we use the friction between the floor and our shoes to prevent us from slipping.
3. If the floor is wet, the friction between the floor and our shoes is reduced. This may cause us to slip.

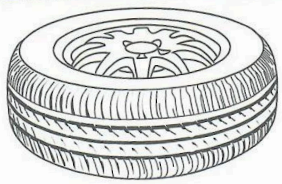
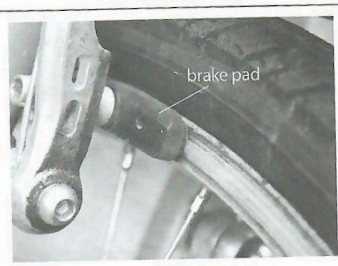
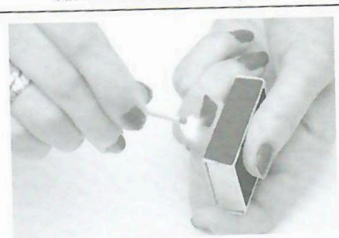
4. **Friction** arises from the *irregularities on the rough surfaces in contact.*



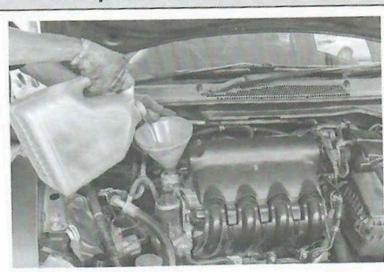
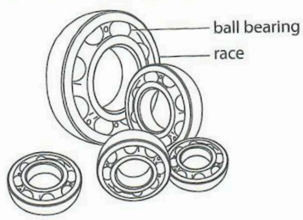
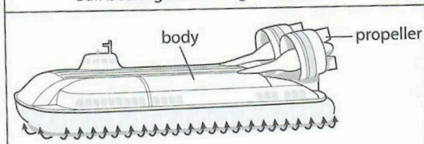
Tip

Another force that opposes motion is air resistance. It is what we feel on our faces when we run fast. It is the reason why a feather falls to the ground slower than a coin.

5. Friction has many *useful purposes* in our world. The table below shows some real-world applications of friction.

Real-world Application of Friction	Desirable Effect(s) of Friction
 Treads on a vehicle tyre	• Car tyres have treads which enable the car to have a **firm grip** of the road. • Shoes also have treads to prevent slipping.
 A bicycle brake	• When a bicycle brake is used, the brake pads press against the wheel frame. Friction is produced which **slows down** the bicycle. • Brakes are also used in other vehicles such as cars.
 An industrial blade sharpener	• Friction is used to **sharpen** the edges of cutting instruments such as kitchen knives and blades.
 Rough surface on a matchbox	• Friction can produce a rapid temperature increase. Striking a matchstick against the rough surface of the matchbox causes the matchstick to light up. • Rubbing your hands together can make them feel warmer.

6. Friction is undesirable in some real-world situations because it can cause *wear and tear* and *undesirable energy loss*. The table shows some examples where friction is not desirable and thus reduced.

Example of Reduction of Friction	Action to Reduce Friction
 Special oil being poured into an engine	• Special oils and grease are used as **lubricants** to reduce the friction between moving parts of an engine.
 Ball bearings in moving machine parts	• **Ball bearings** are used between moving parts of machines such as the bicycle wheel. They can reduce the area of contact.
 Hovercraft moving on a cushion of air	• A **hovercraft** uses propellers to create a layer of air underneath it while travelling to avoid direct contact with the ground.

Worked Example 4.6

A car is moving forward on level ground at a constant speed of 20 m/s. The engine of the car exerts a forward force of 3000 N and the car experiences air resistance of 2000 N and friction *f*.

(a) Find the value of *f*.

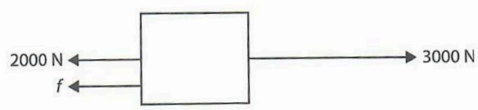
(b) The car suffers a sudden engine problem that reduces the forward force to 1500 N. The air resistance reduces to 1000 N. The constant speed of the car is now reduced to 12 m/s. Find the new value of *f*.

Strategy

(a) As the velocity of the car is constant, the acceleration of the car is zero. Therefore, the net force acting on the car is zero.

(b) Similarly, as velocity is constant, acceleration is zero and consequently net force is also zero. The net force is not dependent on the value of the constant speed.

Solution



(a) Net force $F_N = 0$

$3000\text{ N} = 2000\text{ N} + f$

$f = 3000\text{ N} - 2000\text{ N} = 1000\text{ N}$

(b) $F_N = 0$

$1500\text{ N} = 1000\text{ N} + f$

$f = 1500\text{ N} - 1000\text{ N} = 500\text{ N}$

Explanation

Friction is a force that depends on many factors such as the roughness of the surfaces involved and the speed of motion. Do not assume that friction stays constant unless specified.

Common Error

✗ Friction arises only when the body is moving.

✓ Friction can also arise when the body is stationary.

Explanation

Friction can also be present when a body is stationary as it is preventing the body from moving.

Tip

Remember that friction cannot be completely avoided. However, the effect of friction in many situations is small so it can be ignored for simplicity.

Tip

Skills checklist for this chapter:

- Able to describe how a force can change motion
- Know how to use $F_N = ma$
- Able to describe how balanced and unbalanced forces affect a body
- Know how to identify the action–reaction pair of forces
- Know how to draw free-body diagrams
- Able to describe how friction can be useful (desirable)
- Able to describe how friction can be reduced (undesirable)

Checkpoint 4.3

1. Which of the following is **not** an effect of friction?
   - **A** Friction causes a moving object to move faster.
   - **B** Friction causes a moving object to cool down.
   - **C** Friction causes wear and tear to tyres.
   - **D** Friction causes a knife to be sharper.
2. Which of the following is **not** a useful application of friction?
   - **A** Car engine becoming hotter due to friction between moving parts
   - **B** A weightlifter applying powder on his hands before lifting weights
   - **C** Using a pencil to write on paper
   - **D** Pulling a rope

Test Station ▸▸

1. Figure 4.1 shows the normal forces acting on a stationary book on a table.

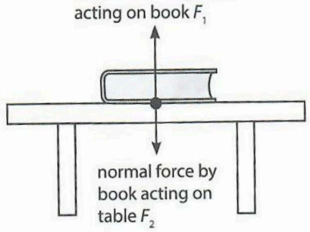


Figure 4.1

Why is $F_1 = F_2$?

A The stationary book tends to oppose change of motion.

B The book is stationary, so its net force is zero.

C They are an action–reaction pair.

D They are balanced forces.

2. Two forces, 5 N and 4 N, are acting on an object. Which of the following forces **cannot** be the net force acting on the object?

A 1 N

B 2 N

C 9 N

D 12 N

3. A car is moving on a horizontal road at a speed of 90 km/h.

(a) When the brakes are applied, a constant friction of 36 000 N acts on the car. Determine the distance travelled after braking if the car takes 8.0 s to come to a stop. Draw a graph if necessary. [3]

(b) Explain why the stopping distance will be greater when the road is wet. [2]

Q 4. A hanging lamp is connected to a cable and hung from the ceiling. A steady horizontal wind is blowing against the lamp. The mass of the lamp is 2.0 kg and the cable makes an angle of 15° with the vertical. Refer to Figure 4.2.

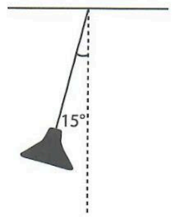


Figure 4.2

(a) Calculate the weight of the lamp if g is 10 N/kg. [1]

(b) Draw a free-body diagram of the lamp. [2]

(c) A stronger horizontal wind blows and the angle increases. How do each of the forces acting on the lamp change? [3]

5. Tyres provide cars with grip so that the cars can move and stop safely.

(a) After some time, the tyres of a car must be replaced with new ones. What is the effect of friction that causes this? [1]

(b) In some countries, metal chains are attached to tyres of a car during winter. Suggest why. [2]