3 Force and Pressure

Study Station ▸▸

A Types of Forces

Learning Outcome

- Identify forces and differentiate between contact forces (e.g. friction, air resistance, tension and normal force) and non-contact forces (e.g. gravitational, electrostatic and magnetic forces).

1. Force is a physics concept used to explain *why stationary objects start to move and why moving objects change their motion.*
2. In football, players try to kick a ball into a net while the opposing goalkeeper tries to stop them.

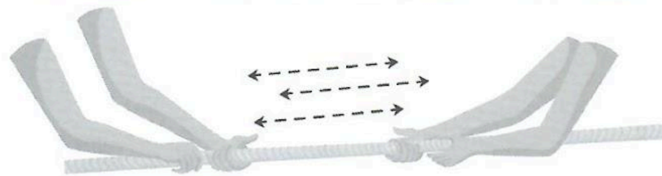
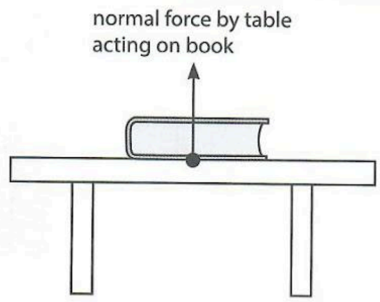
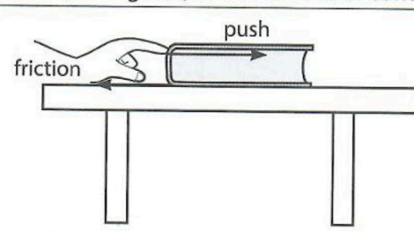
The table lists explanations to some actions carried out during a game of football.

Physical Action	Explanation
A player kicks a stationary ball during a free kick and the ball moves.	A force causes a stationary ball to move.
A goalkeeper stops a ball from going into the net with his hands and holds on to it.	A force causes a moving ball to stop moving (become stationary).
A forward-moving ball is kicked further forward by a player.	A force causes a moving ball to move faster.
A ball moving forward is tapped by a foot, which causes the ball to slow down on the playing surface.	A force causes a moving ball to move slower.
A player heads a ball during a corner kick into the net.	A force causes a moving ball to change direction.

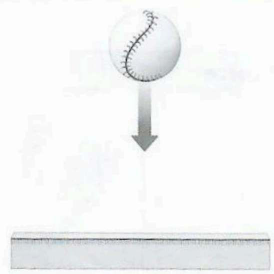
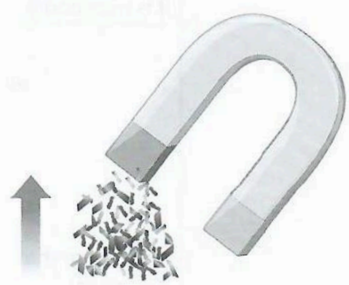
3. Force is a concept that cannot be seen directly (it is not a physical object). However, we can know that forces exist by observing their effects on motions of bodies.

4. We can categorise the forces into either **contact forces** (forces that act between *objects in physical contact*, i.e. touching each other) or **non-contact forces** (forces that *do not require the objects to be in physical contact*, i.e. can occur at a distance).

   • Tension, normal force, friction and air resistance are contact forces. The table shows an example of each.

Contact Force	Example
Tension	 It is a pulling force that arises when a rope is stretched. It is exerted along the rope.
Normal force	 It is a force that arises due to contact between objects. It is perpendicular (90 degrees) to the surface of contact.
Friction	 It is a force that arises due to contact with a rough surface. It opposes motion.
Air resistance	 It is a force that arises due to the motion of objects in air. It opposes the motion.

- Gravitational force, electrostatic force and magnetic force are non-contact forces. The table shows an example of each.

Non-contact Force	Example
Gravitational force	 It is a force that pulls all objects towards Earth.
Electrostatic force	 It is an attractive force between electrically charged objects (balloon and hair).
Magnetic force	 It is a force that attracts iron and steel objects to magnets.

Common Error

Non-contact forces only occur when the objects are not touching each other.

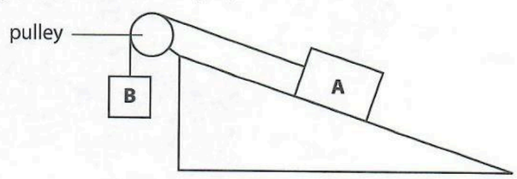
Non-contact forces also occur when the objects are touching each other.

Explanation
For example:
- Gravity still acts on us when we are standing on the surface of Earth and our feet are in contact with the ground.
- Electrostatic force still occurs when the strands of hair are in contact with the surface of the balloon.
- Magnetic force is still occuring when the nail is stuck to the magnet.

Worked Example 3.1

A special type of train called a funicular is pulled by steel ropes and brings people up a hill.

A simple model represents the funicular as block **A** on a smooth inclined surface tied with a string to block **B** over a pulley (a wheel that can spin).



Name all the forces acting on block **A**.

Strategy

Recall the circumstances that bring rise to forces.
Gravitational force pulls down all objects including block **A** towards Earth.
The string is taut, so tension acts on block **A**.
As block **A** is in contact with the inclined surface, it experiences a normal force acting perpendicularly to the inclined surface.
Since the surface is smooth, no friction acts on it.

Solution

Gravitational force, tension and normal force

Link Discover Physics (5th Edition) Textbook — Section 3.1

Checkpoint 3.1

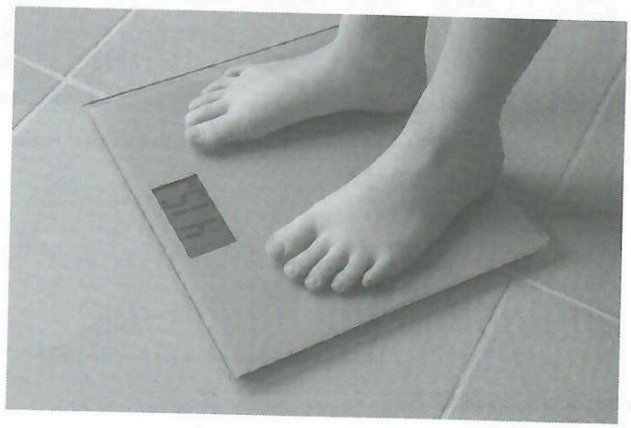
1. What does 'normal' in the term 'normal force' refer to?
   - **A** It refers to the most common type of force.
   - **B** It refers to forces that arise from contact between surfaces.
   - **C** It refers to the direction of the force that is perpendicular to the contact surface.
   - **D** It refers to a force that can occur at any distance.

B Mass and Weight

Learning Outcomes

- State that mass is a physical quantity indicating the amount of matter in a body.
- State that a gravitational field is a region in which a mass experiences a gravitational force.
- Define gravitational field strength, g.
- Recall and apply the relationship *weight = mass × gravitational field strength* to new situations or to solve related problems.
- Differentiate between mass and weight.

1. *Weight is an example of gravitational force*, which pulls all objects towards Earth.
2. When you stand on a weighing scale, you are pushing down on the weighing scale. The weighing scale measures this force as your weight.



3. The **mass** of an object is a measure of the *amount of matter* in the object. Its SI unit is **kilogram (kg)**.
4. The **weight** of an object is the *gravitational force exerted on the object by Earth*. Its SI unit is **newton (N)**.
   - Weight, W of an object is directly proportional to the mass, m of the object.

     $$W = mg$$

     where g is the constant of proportionality with an approximate value of 10 N/kg for objects near Earth's surface
   - The weighing machine measures the weight and calculates the mass using this proportionality. It then displays the calculated mass.

Common Error

✗ Day-to-day conversational speaking:
"My weight is 41.5 kg."

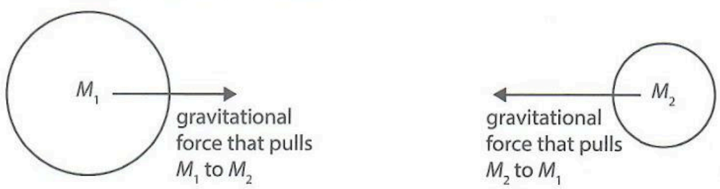
✓ Speaking with correct physics terminology:
"My mass is 41.5 kg."

Explanation
If a person's mass is 41.5 kg, his or her weight will be approximately 415 N.

5. Weight is responsible for all objects falling down towards Earth.

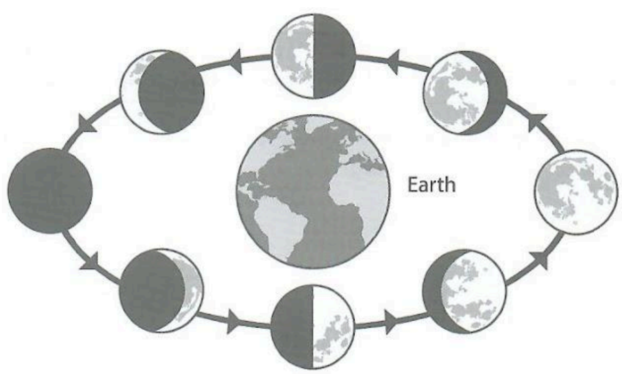
Isaac Newton (lived from 1642 to 1726) thinking about gravitational force under an apple tree

6. Generally, **gravitational force** is the force that *arises between two objects due to their masses.* Its SI unit is **newton** (**N**).
   - Its strength (i.e. magnitude) depends on the masses of both objects. The gravitational forces between the common objects in our daily lives are very weak. Hence, it is usually not noticeable.
   - It is an *attractive* force. It is a **vector quantity**.



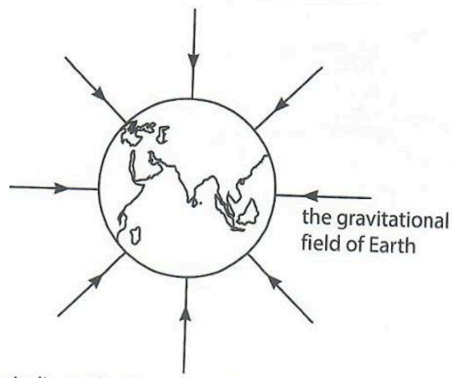
Large masses such as Earth (M_1) and the moon (M_2) are pulling each other. Hence, the moon continues to orbit around Earth.

7. The gravitational force of Earth is responsible for keeping the moon in orbit around Earth. The diagram shows the moon phases as it orbits around Earth.



Moon orbiting round Earth

8. Instead of using the interaction between two masses to understand gravitational force, we can also use the concept of gravitational field.
   - **Gravitational field** is defined as the *region in which a mass experiences a gravitational force*. It is a property of the space.
   - In the example on the previous page, M_1 creates a gravitational field around it. A mass M_2, which is in this field, will experience a gravitational force. Similarly, M_1 experiences a gravitational force because it is in the gravitational field created by M_2.
   - The gravitational field can be represented by lines with arrows.



The arrows indicate the direction of the force that a mass will experience in the gravitational field of Earth.

9. **Gravitational field strength** *g* is defined as the *gravitational force* F_g *per unit mass, m*, experienced at that point. Its SI unit is N/kg.

$$g = \frac{F_g}{m}$$

Its direction is the same as the gravitational force acting on the mass placed at that point. It is a **vector quantity**. The table describes factors that influence gravitational field strength with an example.

Factors Influencing Gravitational Field Strength	Example With Explanation
A larger mass produces a stronger gravitational field.	Earth produces a stronger gravitational field than the moon.
A point nearer to the mass experiences a stronger magnetic field.	Gravitational field at sea level is stronger than at the top of a mountain.

10. Note that gravitational field strength is the same as the constant of proportionality between mass and weight. (Compare $F_g = mg$ with $W = mg$)

Worked Example 3.2

A mountain climber carries a load of mass 20.0 kg.

(a) At 20.0 m above sea level, the weight is measured to be 196.2 N. Calculate the gravitational field strength at this location.

(b) On a mountain at 2000 m above sea level, the weight is measured to be 195.6 N. Explain the apparent loss of weight.

(c) Calculate the weight of a mass of 26.0 kg on the mountain.

Strategy

(a) Recall $g = \frac{W}{m}$.

(b) Note that g depends on the location. Calculate g at this location and compare with g at the previous location.

(c) Use $W = mg$ with the g at that location.

Solution

(a) Gravitational field strength $g = \frac{W}{m}$

$$= \frac{196.2\ \text{N}}{20.0\ \text{kg}}$$
$$= 9.81\ \text{N/kg}$$

(b) New gravitational field strength $g_{new} = \frac{W_{new}}{m}$

$$= \frac{195.6\ \text{N}}{20.0\ \text{kg}}$$
$$= 9.78\ \text{N/kg}$$

The new location, at 2000 m above sea level, is further away from Earth than the previous location (20 m above sea level). The gravitational field strength at the new location is weaker. Thus, the weight measured is less on the mountain.

(c) Weight of mass 26.0 kg is,

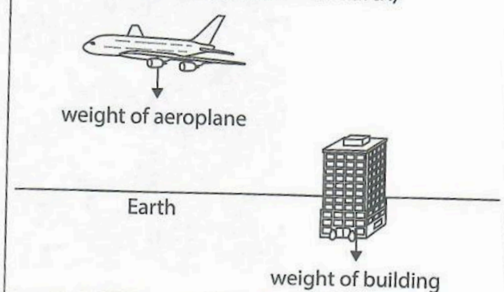
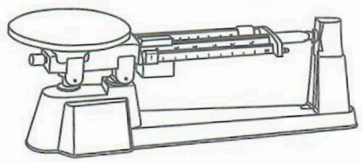
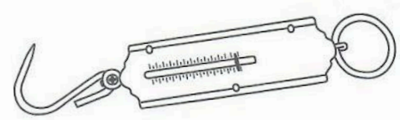
$W = mg$

$= 26.0\ \text{kg} \times 9.78\ \text{N/kg}$

$= 254.28\ \text{N}$

$= 254\ \text{N}$ (3 sig. fig.)

11. In physics, mass and weight are different quantities. The table below lists the differences between mass and weight.

Mass	Weight
Indicates the amount of matter	Indicates the strength of the gravitational force exerted by Earth
Scalar quantity	Vector quantity (downwards direction towards Earth) 
SI unit is kilogram (kg)	SI unit is newton (N)
Independent of location	Dependent on the location (dependent on gravitational field strength at that location)
Measured using a beam balance 	Measured using a spring balance 

Common Error

✗ There is no weight acting on an astronaut who is floating in outer space, i.e. in a state of 'weightlessness'.

✓ Weight acts on all objects and pulls them towards Earth including the astronaut even though he is in outer space.

Explanation

Although the astronaut is floating and does not seem to fall, the astronaut is actually in a circular motion (i.e. orbit) around Earth, which is a combination of free fall and horizontal motion.

Tip

Gravitational field strength, g (covered in this chapter) is equivalent to the acceleration of free fall, g (covered in Chapter 2).

C Density

Learning Outcome

- Recall and apply *density = mass / volume* to real-world situations and solve related problems.

1. The density of an object compared to the density of another object tells us whether the object will float or sink in the other object.

   (a) If the density of the object is *less than the density of the liquid*, it will *float* in the liquid.

Materials that float in water

ball candle cork pencil
rubber egg

rock screw key ring
paper clip coin

Materials that sink in water

   (b) If the density of the object is *more than the density of the liquid*, it will *sink* in the liquid.

Common Misconception

✗ Heavy objects sink.

✓ Whether an object floats or sinks does not depend on its mass or weight but on its relative density.

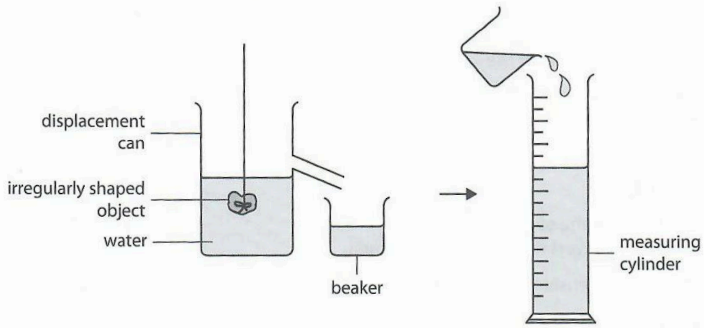
2. **Density ρ** (Greek letter 'rho', pronounced as 'roh') is defined as the **amount of mass m per unit volume V**.

$$\rho = \frac{m}{V}$$

   - Its SI unit is **kilogram per cubic metre** (kg/m^3). It is also common to use the unit g/cm^3 (1 g/cm^3 = 1000 kg/m^3).
   - It is a scalar quantity.

3. We can determine the *mass m* of an object by measuring with a *beam balance*.

4. We can determine the *volume V of an irregularly shaped object* by measuring the *volume of water displaced* when the object is fully submerged in water.

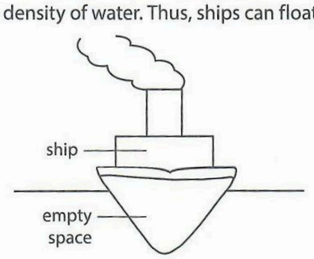


- In a displacement can, submerge an irregularly shaped object in water.
- Collect the displaced water in a beaker and pour it into a measuring cylinder to measure the volume.

5. Average density of an object is given by the total mass divided by the total volume.

$$\text{Average } \rho = \frac{\text{total } m}{\text{total } V}$$

- The density of metals, such as steel, is greater than the density of water, so bars made of metal sink in water.
- Ships consist of metal which has been shaped to contain an empty space so that the average density is smaller than the density of water. Thus, ships can float on water.



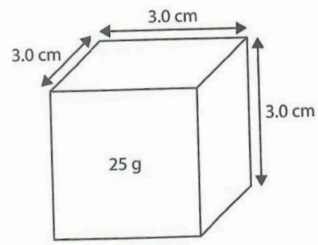
The shape of the ship increases its total volume without increasing its total mass.

Worked Example 3.4

An ice-making machine is designed to produce ice cubes of side 3.0 cm and mass of 25 g.

(a) Calculate the density of the ice cubes in kg/m^3.

(b) The design has been changed to produce bigger ice cubes with sides twice as long. Calculate the mass of the bigger ice cube in kg.



Strategy

(a) Recall that volume of a cube is given by $V = length^3$. Convert the units to SI units first.

(b) Note that the densities of the smaller ice cube and larger ice cube are the same.

Solution

Volume of ice cube $V = l^3$

$= (3.0\ cm)^3$

$= (0.030\ m)^3$

$= 2.7 \times 10^{-5}\ m^3$

Mass of ice cube $m = 25\ g$

$= 2.5 \times 10^{-2}\ kg$

Density of ice cube $\rho = \frac{m}{V}$

$= \frac{2.5 \times 10^{-2}\ kg}{2.7 \times 10^{-5}\ m^3}$

$= 925.93\ kg/m^3$

$= 926\ kg/m^3$ (3 sig. fig.)

Volume of bigger ice cube $V_{bigger} = l^3_{bigger}$

$= (2 \times 3.0\ cm)^3$

$= 2^3 \times (0.030\ m)^3$

$= 8 \times 2.7 \times 10^{-5}\ m^3$

$= 2.16 \times 10^{-4}\ m^3$

Mass of bigger ice cube $m_{bigger} = \rho V_{bigger}$

$= 925.93\ kg/m^3 \times 2.16 \times 10^{-4}\ m^3$

$= 0.20\ kg$

Explanation

Note that if the length of each side is multiplied by 2 (side is twice as long), the volume becomes multiplied by 8 (2^3).

Link Discover Physics (5th Edition) Textbook — Section 3.3

Checkpoint 3.3

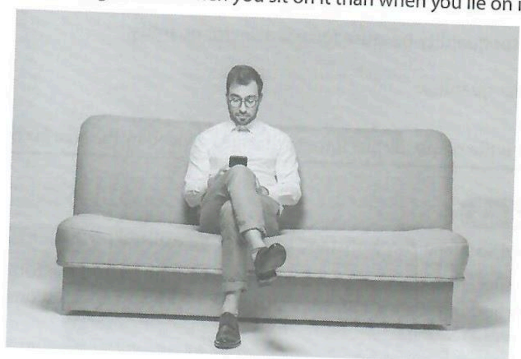
1. Convert the density of water, 1 g/cm^3 to kg/m^3.

D Pressure

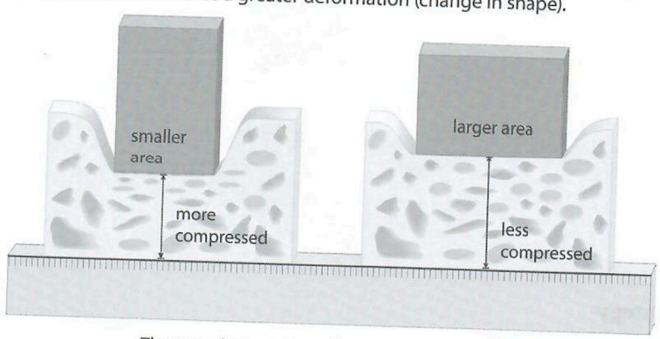
Learning Outcomes

- Define pressure using force and area.
- Recall and apply *pressure = force / area* to real-world situations and solve related problems.

1. Pressure is a *measure of how a force can change the shape of an object or body.*
2. The shape of the sofa changes more when you sit on it than when you lie on it.



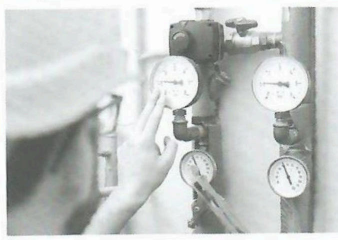
- Whether you sit or lie on the sofa, the force that you exert on the sofa is the same, i.e. equal to your weight. Thus, force alone does not explain the difference in the change of shape.
- When you sit rather than lie on the sofa, you are applying a force to a smaller area. The force is more concentrated and causes a greater deformation (change in shape).



The same force on a smaller area causes a greater deformation (more compression).

4. Pressure can be measured by special devices depending on the situation.
   - A blood pressure monitor measures the pressure in our blood vessels. A high value indicates a higher risk of encountering health problems such as heart attack.

   - In industries, pressure meter gauges measure the pressure of gases in pipes and tanks.



Tip

Summary notes for this chapter:

- Force causes
  (i) stationary objects to start moving and
  (ii) moving objects to change motion. Its SI unit is newton (N).
- Examples of contact forces are friction, air resistance, tension and normal force.
- Examples of non-contact forces are gravitational, electrostatic and magnetic forces.
- The mass *m* of an object is a measure of the amount of matter in the object. Its SI unit is kilogram (kg).
- The weight *W* is gravitational force (pull) by Earth. The formula to find weight of an object is $W = mg$. Its SI unit is newton (N).
- Gravitational field strength, $g = \frac{F_g}{m}$. Its unit is N/kg.
- Density $\rho = \frac{m}{V}$. Its SI unit is kilogram per cubic metre (kg/m^3).
- Pressure $P = \frac{F}{A}$. Its SI unit is pascal (Pa) or N/m^2.

Link Discover Physics (5th Edition) Textbook — Section 3.4

Checkpoint 3.4

1. A man of mass 80 kg is sitting on a chair. The total area of contact between the man and the chair is 0.020 m^2. Calculate the pressure exerted on the chair by the man.

3. **Pressure *P*** is defined as the **force *F* acting per unit area *A***.

$$P = \frac{F}{A}$$

- Its SI unit is **pascal (Pa)** or **newton per square metre (N/m^2)**.
- It is a *scalar quantity*.

Common Error

✗ Pressure is a vector quantity because force is a vector quantity.

✓ Pressure is a scalar quantity.

Explanation
The pressure at a point is the perpendicular force to that area divided by the area in contact.

Worked Example 3.5

A chair is designed so that it can withstand the pressure exerted on it.

When a lady sits on a chair, she exerts a force of 600 N on the chair. If the total area of contact between the lady and the chair is 150 cm^2, calculate the pressure exerted on the chair by the lady. Express your answer in SI units.

Strategy
Firstly, convert all units to SI units before substituting the values into the formula.

Solution
Area $A = 150\ cm^2$

$= 150 \times 10^{-4}\ m^2$

$= 1.50 \times 10^{-2}\ m^2$

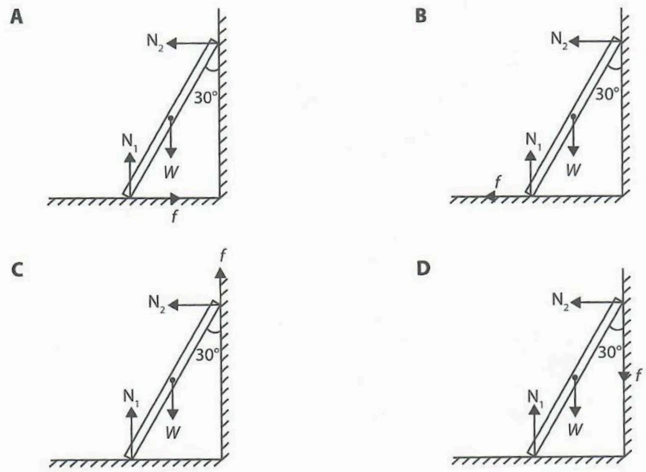
Pressure $P = \frac{F}{A}$

$= \frac{600\ N}{1.50 \times 10^{-2}\ m^2}$

$= 4.00 \times 10^{4}\ N/m^2$

Test Station ▸▸

1. A stationary uniform ladder of length 6 m and mass 20 kg is leaning against a smooth vertical wall on rough ground. The ladder makes an angle of 30° with the vertical. Which of the following diagrams **correctly** shows the forces acting on the ladder?



2. In Figure 3.1, lines with arrowheads are used to illustrate a gravitational field.

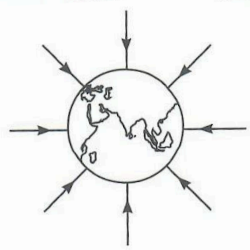


Figure 3.1

Which of the following statements is **not** correct?

A Gravitational field lines show the direction of the weight of an object at any point.

B Gravitational field strength is defined as the gravitational force acting on 1 kg of mass at any point.

C The gravitational field is stronger at points nearer to Earth.

D The gravitational field ends at a certain distance from Earth.

3. A recipe to bake a simple cake requires the following ingredients:
   - 7 eggs
   - 600 g wheat flour
   - 500 m*l* sugar

   The density of sugar is about 0.8 g/cm^3. Calculate the mass of sugar used in this recipe. (1 m*l* is equivalent to 1 cm^3.)

   A 40 g

   B 62.5 g

   C 400 g

   D 625 g

4. One of the largest passenger aeroplanes is the double-decker Airbus 380, which can carry up to 853 people (Figure 3.2). A certain airline allows a maximum baggage of 30 kg per traveller.

Figure 3.2

(a) An engineer estimates that the average mass per traveller is 100 kg. Calculate the total weight to be carried by the aeroplane at maximum capacity. Give your answers in 2 significant figures. (Take *g* as 10 N/kg) [2]

(b) Explain why this total weight decreases when the aeroplane flies. [2]

5. An agricultural helicopter drone is used to spray fertiliser over a farm (Figure 3.3).

Figure 3.3

The drone is hovering at a constant height above the ground. The weight of the drone is 600 N. The drone has a rotor system which generates an upward force known as lift. (Take *g* as 10 N/kg.)

(a) Calculate the mass of the drone. [2]

(b) The area of the rotor blades is 1.2 m^2. Calculate the pressure exerted on the rotor blades by the air. [2]