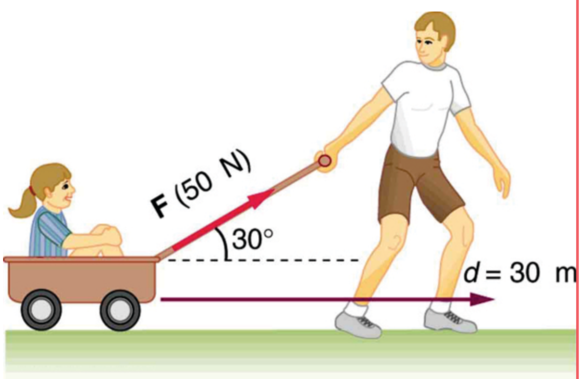
Unit - 5

FORCES AND MATTER

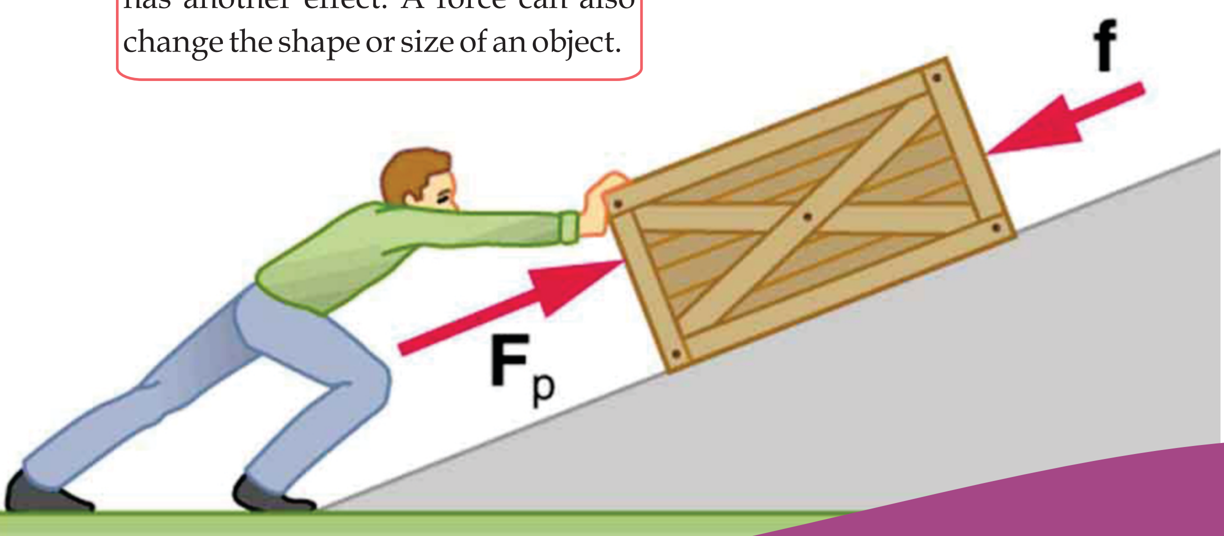


Students Learning Outcomes (SLOs)

After learning this unit students should be able to:

- Use forces to change the shape and size of the body
- Carry out experiment to produce extension against load graph
- Interpret extension against load graph
- Define Hooke's law
- Calculate extension in spring and spring constant using formula $F = kx$
- Define and explain pressure
- Understand the factors that affects the pressure
- Calculate the pressure using formula $p = F/A$
- Understand hydraulic machines

You can not see force, but you can see what it does. You have learnt that how force can change the motion of objects. Force can make the object speed up, slow down, start moving, stop or change direction. But force has another effect. A force can also change the shape or size of an object.



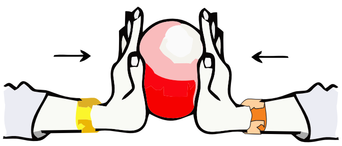


Fig 5.1 (a)

- Force is needed to move a car.
- Force causes the spring to stretch.
- We need force to move some luggage.
- If you bend your plastic ruler you will change its shape.

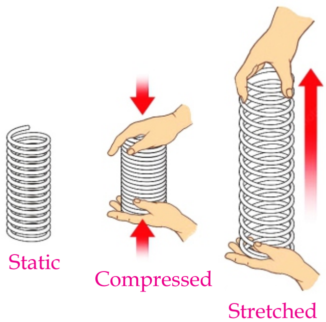


Fig 5.1 (b)

Force applied by hands on the dough changes its shape; Fig 5.1 (a). A spring can be stretched or compressed by applying force; Fig 5.1 (b).

Notice that, what effect a force has, depends on the materials involved. Soft materials, such as rubber can bend and flex very easily. A spring comes back to its original shape when you remove the force. Materials like this are called elastic.

When force is exerted on area, this is known as pressure; Fig 5.1 (c).

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

Fig 5.1 (c)

As you have already studied that hydraulic machines also work on principals of fluid pressure. Hydraulic breaks are used almost in all vehicles. They cause a relatively small force from the driver's foot to be multiplied to produce a greater force, which acts equally on all four brake pads.

Force

Force can be defined as

A push or a pull that changes or tends to change the state of rest or uniform motion of an object or changes the direction or shape of an object.

5.1 FORCES ACTING ON SOLIDS

Solids have definite shapes and sizes, however it is possible to change their shapes and sizes by applying external forces. When the external force is removed, the object tends to return to its original shape and size. This behavior is called elastic behaviour. Solids can be stretched, squashed, bend or twisted Fig 5.2 (a, b). These figures show the different ways in which elastic behavior of solid objects can be demonstrated. A sufficiently large force will permanently deform or break an object Fig 5.2 (c).

Fig 5.2(a)
A Force can bend an object

Fig 5.2(b)
A Force can twist an object

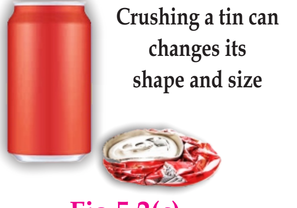


Fig 5.2(c)
A force can deform an object

5.2 STRETCHING SPRINGS

As springs are designed to stretch a long way when force is applied, therefore it is easy to measure changes in their lengths.

To explain how solids are deformed? let us perform an experiment with the spring.

Consider a spring hung from a rigid support, so that its top end is fixed; Fig 5.3 (a). Weights are hung on other end of the spring. These are called load. As load is increased, the spring is stretched and its length increases.

When the load is removed, the spring returns to its original length. This is called elastic change. When the load is increased in regular steps the length of the spring also increases simultaneously Fig 5.3 (b). If the load is increased greatly, the spring will change its shape permanently.

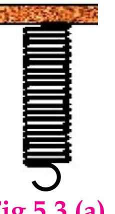


Fig 5.3 (a)
unstretched spring

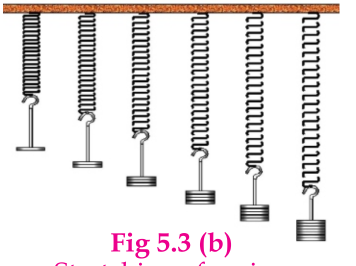


Fig 5.3 (b)
Stretching of spring

Extension of spring

The length of spring increases as the force (load) increases; Fig 5.3 (b). This increase in length of spring is

Do You Know!

When you pull on the band, it stretches but doesn't break. The resistance you feel when you pull on it is elastic force. The farther you stretch the band, the greater the elastic force. After you stop pulling the band, it returns to its original shape.

known as extension. Hence

Length of stretched spring = Original length + Extension

Let's carry out an experiment to stretch a spring of original length 20cm. Table 5.1 shows recorded result of this experiment. The first column shows the increase in load in regular steps. Second column shows the increase in length of stretched spring. Third column shows the value of extension, due to change in length in each step.

Table 5.1 for load and extension

Load (N)	Length (cm)	Extension (cm)
0.0	20	0.0
2.0	21	1.0
4.0	22	2.0
6.0	23	3.0
8.0	24	4.0
10	25	5.0
12	26	6.0
14	28	8.0
16	30	10

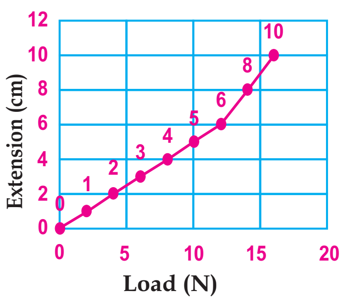


Fig 5.3 (c)
Graph between load and extension

Table 5.1 shows how a spring stretches as the load on it increases. Dependance of extension on load, shown in Fig 5.3 (c).

you can see that the graph has two parts.

- At first, the graph slopes up steadily. This shows that the extension increases in equal steps as the load increases. This behaviour can also be observed in table 5.1
- Then the graph bends. This happens when the load is greater enough to damage the spring permanently. As a result the spring will not return to its original length.

Self Assessment Questions:

Q1: An elastic spring is 70cm long. When it is stretched by hanging some load its length increases to 100cm. Calculate its extension?

Q2: Table 5.2 shows the results of an activity to stretch an elastic spring. Complete the table and draw a graph to represent this data.

Table 5.2: for load and extension

Load (N)	Length (cm)	Extension (cm)
0.0	30	0.0
1.0	32	
2.0	34	
3.0	36	
4.0	38	
5.0	40	
6.0	41.5	
7.0	42	
8.0	43	

5.3 Hooke's law

Robert Hooke, an English scientist first described the mathematical pattern of stretching a spring. He observed the dependence of displacement or size of the deformation upon the deforming force or load. Hooke's law states that:

Within elastic limit, the displacement produced in the spring is directly proportional to the force applied.

Quick Lab

Investigating the spring:

1. Hang some weights(load) to stretch the spring.
2. Note down the extension in the spring.
3. Increase the weight(load) gradually of equal magnitudes.
4. Note down corresponding reading of extension.
5. Make a table of load and extension.
6. Plot a graph between load and extension to obtain the behavior (pattern) of the spring.

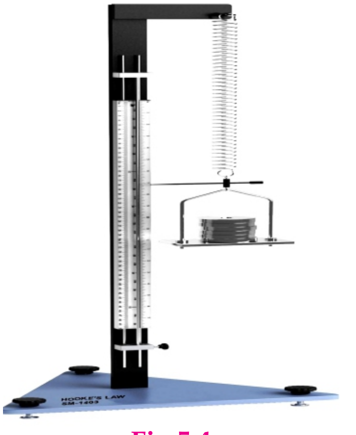


Fig 5.4
Extension in the spring depends upon the load.

Do You Know!

ELASTICITY

Elasticity is the property of a body to regain its original shape and size when deforming forces are removed.

Do You Know!

Material	Young's Modulus (in GPa)
Brass	91
Copper	120
Mild steel	210
Plastic	2
Rubber	0.02

Where 1GPa = 10^9Pa

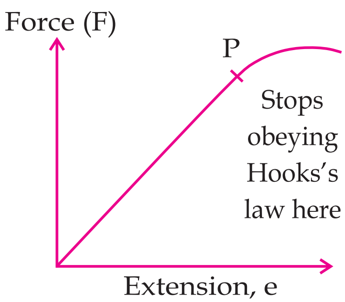


Fig 5.5
Graph between force and extension.

Do You Know!

Why springs?

Robert Hooke a scientist and inventor was interested in springs for two reasons.

1. Spring are useful in making balances. Hooke wanted to make a very sensitive and accurate weight machine or balance.
2. He also realised that a spiral spring could be used to control a clock or wrist watch.

Mathematically if 'F' is the applied force and 'x' is the displacement (extension) in the spring then the equation for Hooke's law may be written as:

$$F \propto x$$

or $$F = kx \quad \text{.......................(5.1)}$$

where k is spring constant (stiffness of spring).

Hooke's law is applicable to all kinds of deformation and all types of matter i.e., solids, liquids or gases within certain limit. This limit tells the maximum force or stress that can be safely applied on a body without causing permanent deformation in its length, volume or shape. In other words, it is a limit within which a body recovers its original length, volume or shape after the deforming force is removed. Beyond this limit spring deforms permanently; Fig 5.5.

Worked Example 1

A spring has spring constant $k = 30\ Nm^{-1}$. What load is required to produce an extension of 4 m?

Solution

Step:1 Write down known quantities and the quantities to be found.

$k = 30\ Nm^{-1}$

$x = 4\ m$

$F = ??$

Step:2 Write down formula and rearrange if necessary

$F = kx$

Step:3 Put the values in formula and calculate

$F = 30Nm^{-1} \times 4m$

$F = 120N$

Hence 120N load is required to stretch the spring by 4m.

Self Assessment Questions:

Q3: How much force is needed to pull a spring to a distance of 30cm, the spring constant is 15 Nm^{-1}?

Q4: Write two properties of spring.

5.4 Pressure

Press a pencil from its ends between the palms; Fig 5.6.

Fig 5.6

The palm pressing the tip feels much more pain than the palm pressing its blunt end. We can push a drawing pin into a wooden board by pressing it by our thumb; Fig 5.7. It is because the force we apply on the drawing pin is confined just at a very small area under its sharp tip. A drawing pin with a blunt tip would be very difficult to push into the board due to the large area of its tip.

Fig 5.7
A drawing pin with a sharp tip enters easily when pressed.

In these examples, we find that the effectiveness of a small force is increased if the effective area of the force is reduced.

The area of the tip of pencil or that of the nail is very small and hence increases the effectiveness of the force. The quantity that depends upon the force and increases with decrease in the area on which force is acting is called pressure. Thus, pressure is defined as

The force acting normally per unit area on the surface of a body is called pressure.

Thus,
$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

$$P = \frac{F}{A} \quad \text{......................(5.2)}$$

How to calculate pressure

If F is the magnitude of a force exerted perpendicular to a given surface of area A, then the pressure P equals to the force divided by the area:

Do You Know!

The pressure exerted by the air molecule at sea level is measured in atmosphere; where:

1 atmosphere = 1.013×10^5 Pascal

$\therefore$ 1 atm = 1.013×10^5 Pa

Do You Know!

Why an acrobat does not hurt when he lied down on the bed of nails?
There is no miracle in this trick. We know that pressure is defined as force per unit area. If you step up on a nail, the entire body weight exerts more pressure because the area of nail tip is very small. In case of bed nails, the pressure exerted by weight of body is distributed on the hundreds or thousands of nails lying close to each other. Thus, net pressure on a nail is very small. Hence, an acrobat does not hurt when he lied down on the bed of nails.

An acrobat laying on bed of nails

$$P = F/A$$

As the force is measured in newtons (N) and area in square meters (m^2). Therefore in SI system unit of pressure is newton per square meter (Nm^{-2}). It is also known as Pascal (Pa):

$$1\ Pa = 1\ Nm^{-2}$$

High pressure, low pressure

The pressure under the studs on the soles of football shoes is high enough to sink into the ground, which gives extra grip. Ice skates have blades in the part that is in contact with ice. Therefore the skater's weight is concentrated on a small area. The effect of this high pressure melts ice just below the blades. This gives the thin film of water, which provide lubrication for the skate to skim over the ice. As the skate moves on, the water re-freezes. On very cold days, the pressure may not be enough to melt the ice, and skating is impossible. An elephant has broad soles to reduce the pressure exerted on the ground. Wide shoulder pads of school bag reduce pressure on the student's shoulder.

Self Assessment Questions:
Use the idea of pressure to explain the following.
Q5: Sharks and crocodiles have sharp teeth.
Q6: Camels have wide, flated feet.
Q7: If you walk on wooden floor wearing shoes with very narrow heels, you will damage the floor.

Pressure in fluids

A fluid is a collection of molecules that are randomly arranged and held together by weak cohesive forces and by forces exerted by the walls of a container. Both liquids and gases are fluids. The pressure exerted by fluids is known as fluid pressure. It acts in all directions. This is because the molecules of fluids move around in all directions, causing pressure on every surface they collide with. A swimmer in swimming pool experience the pressure by water which pushes the swimmer from all sides Fig 5.8. The arrows represent the direction and magnitude of the forces exerted at various points on the swimmer. Note that the net underneath force is larger due to greater depth, giving a net upward or buoyant force that is balanced by the weight of the swimmer.

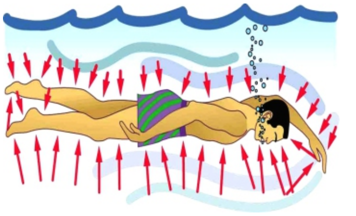


Fig 5.8
Swimmer feels fluid pressure in swimming pool

Factors affecting pressure

Pressure **P** is proportional to the depth, the deeper one dives into water, greater will be the pressure. Twice the depth means twice the pressure (Fig 5.9).

Similarly, pressure also depends upon the density of the material. If a material is five times denser than water, the pressure will be five times greater.

At a depth h in a fluid of density ρ, the pressure p can be written as:

Pressure = depth × density × acceleration due to gravity

$$p = d\rho g \quad \text{.......................(5.3)}$$

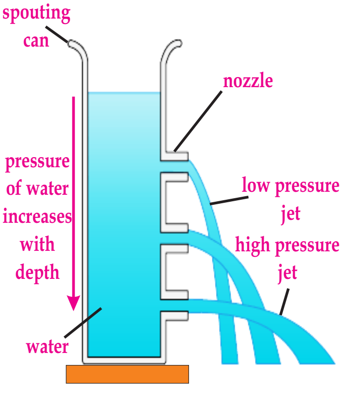
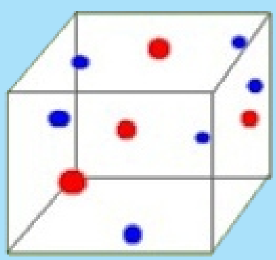


Fig 5.9
Pressure increases with depth

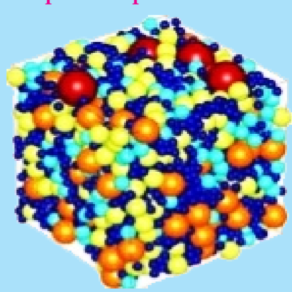
Do You Know!

What is Density?

- Density tells us how tightly matter is packed together.
- If something is packed very tightly together it is considered to be "dense".



More dense sinks and pushes up less dense.



Worked Example 2

Calculate the pressure at a depth of 3m in a swimming pool?

(density of water = $1000kgm^{-3}$).

Step 1: Write down known quantities and quantities to be found.

$d = 3m$

$\rho = 1000kgm^{-3}$

$g = 10ms^{-2}$

$p = ??$

Step 2: Write down formula and rearrange if necessary

$p = d\rho g$

Step 3: Put the values in formula and calculate

$p = 3m \times 1000kgm^{-3} \times 10ms^{-2}$

$p = 30000pa = 3.0 x \times 10^4 pa$

Hence 3.0×10^4pa pressure will be observed at a depth of 3m in the swimming pool.

Worked Example 3

A boy is digging a hole with spade of edge 0.1 cm^2. Calculate the pressure when he is exerting the force of 1000N onto the spade.

Step 1: Write down known quantities and quantities to be found.

$F = 1000N$

$A = 0.1cm^2 = \frac{0.1}{100x100} m^2 = 1.0 x 10^{-5} m^2$

$p = ??$

Step 2: Write down formula and rearrange if necessary

$p = F/A$

Step 3: Put the values in formula and calculate

$$p = \frac{1000N}{1.0 \times 10^{-5} m^2}$$

$$p = 1.0 \times 10^{8} Nm^{-2}.$$

Hence, there will be $1.0 \times 10^{8} Nm^{-2}$ pressure.

Self Assessment Questions:

Q8: A wooden block of dimensions 0.5m×0.6m×1.0m kept on the ground has a mass of 200kg. Calculate the maximum pressure acting on the ground.

Q9: If the density of sea water is 1150 kgm^{-3}, calculate the pressure on a body of 50m below the surface of sea?

Q10: Dam holds water at high altitude. The walls of the dam are made wider at the base. Explain why?

Hydraulic Machine

The machine in which force is transmitted by liquids under pressure is known as hydraulic machine. By the application of relatively small force they produce a greater force.

Pascal's law

The liquid pressure at the surface of the liquid increases when an external force is applied on the surface of the liquid. The increase in the liquid's pressure is transmitted equally in all directions, in similar way it is transmitted equally to the walls of the container in which it is filled. This result leads to a law known as Pascal's law. This law may be stated as:

The pressure applied externally at any point of a liquid enclosed in a container is transmitted equally to all parts of the liquid in container.

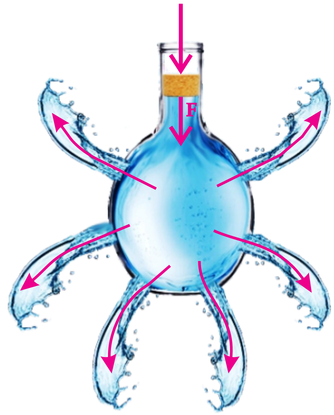


Fig 5.10
Demonstrating pascal's law

It can be demonstrated with the help of a water filled glass vessel having holes around its surface; Fig 5.10. When you apply force through the piston the water rushes out of the holes with the same pressure. The force applied on the piston exerts pressure on water. This pressure is transmitted equally throughout the liquid in all directions. In general, this law holds good for fluids both for liquids as well as gases.

A hydraulic machine works on this principle. Hydraulic brakes, car lifts, hydraulic jacks, forklifts, and other machines make use of this principle.

A hydraulic press is made of two pistons connected by a liquid-filled pipe as shown in Fig 5.11 .

A force of magnitude F_1 is applied to a small piston of surface area A_1. The pressure is transmitted through an incompressible liquid to a larger piston of surface area A_2. Because the pressure must be the same on both sides,

$$p = \frac{F_1}{A_1} = \frac{F_2}{A_2} \quad \text{.......................(5.4)}$$

Therefore, the force F_2 is greater than the force F_1 by a factor A_2/A_1.

By designing a hydraulic press with appropriate areas A_1 and A_2, a large output force can be applied by means of a small input force.

Each side of this equation is the work done by the force. Thus, the work done by F_1 on the input piston equals to the work done by F_2 on the output piston. Thus the principle of conservation of energy applies in the hydraulic press.

Force increases with hydraulics
$F_2=F_1 \times (A_2/A_1)$

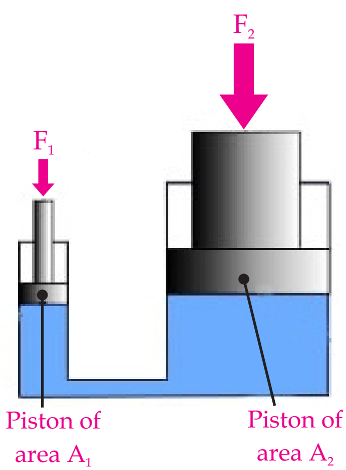


Fig 5.11
A Hydraulic machine

Worked Example 4

In a hydraulic lift system, what must be the surface area of a piston. If a pressure of 300 kpa is used to provide an upward force of 2000 N?

Solution

Step:1 Write down known quantities and quantities to be found.

$p = 300kPa = 300\times1000Pa = 300000Pa = 300000Nm^{-2}$

$F= 2000N$

$A=?$

Step:2 Write down formula and rearrange if necessary

$$p= F/A$$

$$A= F/p$$

Step:3 Put the values in formula and calculate

$A= 2000N/ 300000Nm^{-2}= 0.00667m^2$

Hence the surface area of piston is $0.00667m^2$.

Self Assessment Questions:

Q11. In a hydraulic press, a force of 100 N is applied on the pump of cross-sectional area $0.01m^2$. Find the force that compresses a cotton bale placed on larger piston of cross-sectional area $1m^2$.

Q12. Write down the names of four machines that you have seen working on the principle of pascal's law.

SUMMARY

- Forces on an object can cause tensile deformation (stretching) and compressive deformation (squashing).
- An elastic change occurs when an object returns to its original shape and size after the load is removed.
- An extension against load graph shows how a body stretches when a load is applied to it.
- Hooke's Law: The extension in spring is proportional to the load applied to it, provided the limit of elasticity is not exceeded.

$$F = kx$$

- An extension against load graph is a straight line up to the limit of proportionality.
- Pressure is greater when a large force acts on small area.

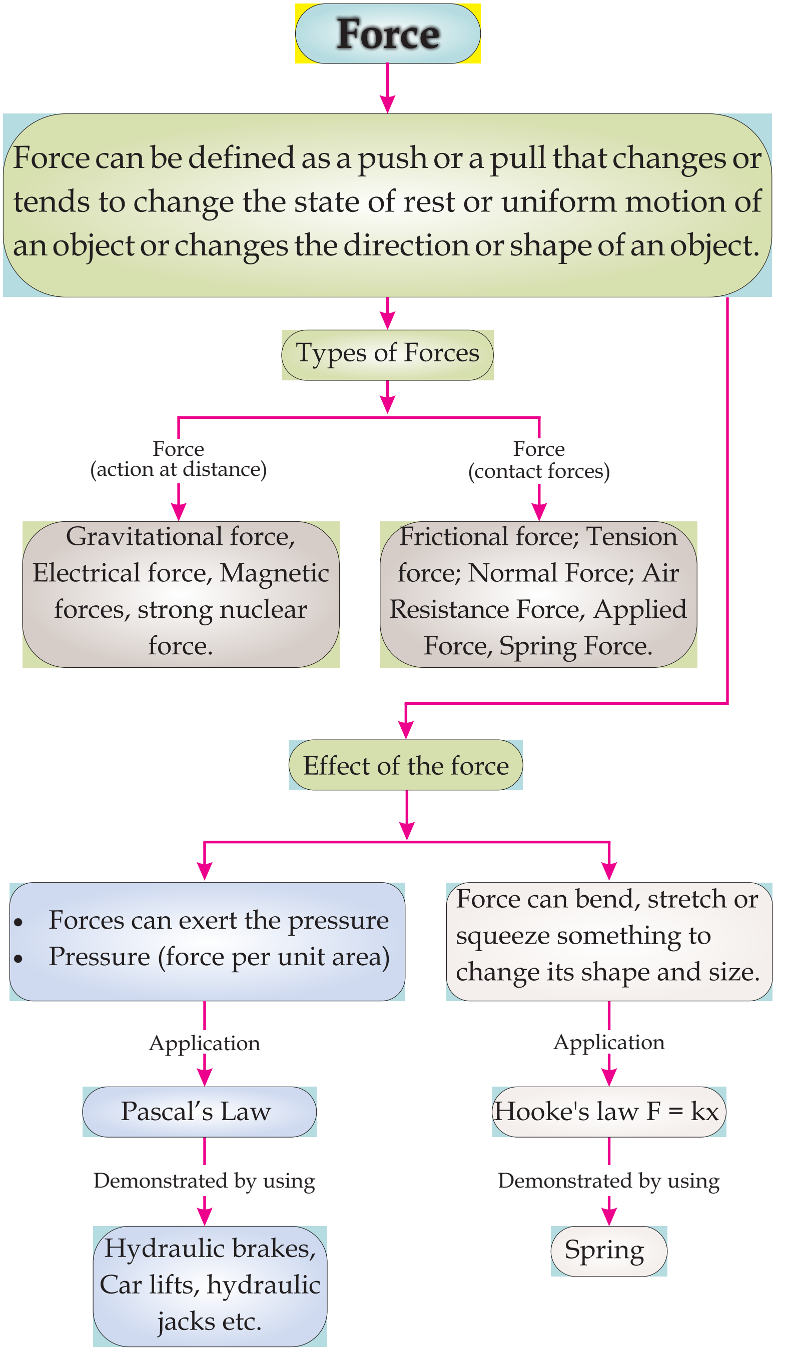
$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

- The pressure in a fluid is greater with large depth, and high density.
- Pressure = depth x density x acceleration due to gravity

$$p = d\rho g$$

- Liquids transmit pressure equally in all directions. This is called Pascal's law.
- The machine in which force is transmitted by liquids under pressure is known as hydraulic machine.

CONCEPT MAP


Force
Force can be defined as a push or a pull that changes or tends to change the state of rest or uniform motion of an object or changes the direction or shape of an object.
Types of Forces
Force (action at distance)
Force (contact forces)
Gravitational force, Electrical force, Magnetic forces, strong nuclear force.
Frictional force; Tension force; Normal Force; Air Resistance Force, Applied Force, Spring Force.
Effect of the force
• Forces can exert the pressure
• Pressure (force per unit area)
Force can bend, stretch or squeeze something to change its shape and size.
Application
Application
Pascal's Law
Hooke's law F = kx
Demonstrated by using
Demonstrated by using
Hydraulic brakes, Car lifts, hydraulic jacks etc.
Spring

End of Unit Questions

Section (A) Multiple Choice Questions (MCQs)

1. The springs in brakes and clutches are used
   a) To restore original position
   b) To measure forces
   c) To absorb shocks
   d) To absorb strain energy
2. If the material recovers the original dimensions, when an external force is removed, this deformation is known as ______ deformation.
   a) Inelastic b) Permanent
   c) Elastic d) Irreversible
3. Which of the following material is more elastic?
   a) Rubber b) Glass
   c) Steel d) Wood
4. If a spring stretches easily then its spring constant has ______.
   a) Large value b) Small value
   c) Constant Value d) Both (a) and (b)
5. What is the unit for the spring constant?
   a) Nm b) Nm^{-2}
   c) Nm^{-1} d) Nm^{2}
6. The spring obeys Hooke's law for the earlier extensions and when the spring becomes damaged it does not appear to do so; Fig 5.12. Estimate, from graph, after addition of which weight the spring damaged.
   a) 1.5 N b) 8 N
   c) 1.6 N d) 2.0 N
7. Which of the following is not a unit of pressure?
   a) Pascal b) Bar
   c) Atmosphere d) Newton

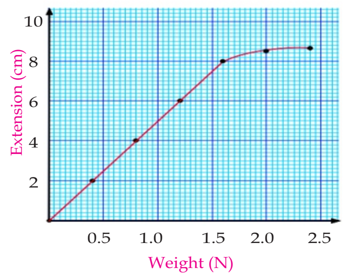


Fig 5.12
Graph between weight and extension for spring

8. If a metal block applies a force of 20 N on an area of 5 cm^2. Find the pressure being applied by the block on the area of ____.
   a) 100 Ncm^{-2} b) 0.8 Ncm^{-2}
   c) 0.25 Ncm^{-2} d) 4 Ncm^{-2}

9. The Fig 5.13 shows a container with three spouts. The container is filled with water. Jets of water pour out of the spouts. Why does the jet of water from the bottom spout goes farthest out from the container?
   a) Pressure decreases with depth.
   b) Pressure increases with depth.
   c) More water available to flow out from the bottom.
   d) Density of water different at different places.

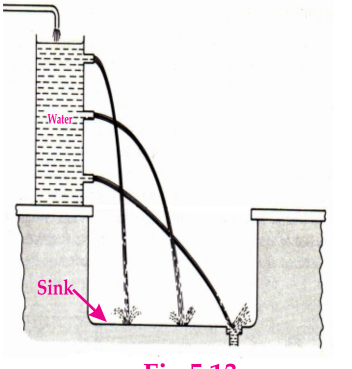


Fig 5.13

Section (B) Structured Questions

Stretching of Spring

1. Some students experimented to find out how a spring stretched when loads were added to it

Table 5.3 For load and extension

Load (N)	0	2	4	6	8	10	12	14
Extension (mm)	0	15	30	45	60	75	90	100

   a) Use these results to plot a graph. (Plot x = load, y = extension in spring).
   b) Use your graph to find
      i) The extension when the load is 3 N;
      ii) The load which produces an extension of 40mm.

2. The variation in extension x of the force F for a spring is shown in Fig 5.14. The point L on the graph is the elastic limit of the spring.
   a) Describe the meaning of elastic limit.

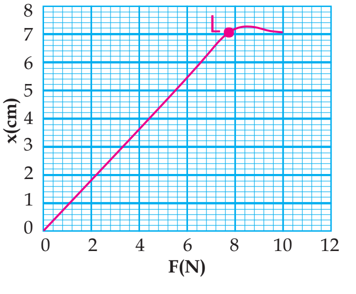


Fig 5.14
Graph between force loadand extension

b) Calculate the force in extending the spring to its elastic limit 'L'.

Hooke's Law

3. State Hooke's law.
4. Calculate the spring constant for a spring which extends by a distance of 3.5cm when a load of 14N is hung from its end.
5. Table 5.4 shows the results of an experiment to stretch a spring.

Table 5.4 For load and extension in spring

Load (N)	Extension (cm)
0.0	0.0
2.0	80.0
4.0	83.0
6.0	86.0
8.0	89.0
10.0	92.0
12.0	93.0

a) Use the result to plot an extension against load graph.
b) On the graph mark the limit of proportionality and state the value of the load at this point.
c) Calculate the spring constant k.
d) Show maximum force at which hooke's law is applicable.

Pressure

6. a) Define the term pressure.
b) Write down the S.I unit of pressure.

7. Why does pressure increases as you dig deeper; Explain in detail.
8. A boy is pressing a thumbtack into a piece of wood with a force of 20 N. The surface area of head of thumbtack is $1cm^2$ and the cross-section area of the tip of the thumbtack is $0.01cm^2$. Calculate
   a) The pressure exerted by boy's thumb on the head of thumbtack.
   b) The pressure of the tip of the thumbtack on the wood.
   c) What conclusion can be drawn from answers of part (a) and (b)?
9. The Fig 5.15 shows a basic hydraulic system that has small and large pistons of cross section area of 0.005 m^2 and 0.1 m^2 respectively. A force of 20N is applied to small piston. Calculate
   a) The pressure transmitted into hydraulic fluid.
   b) The force at large piston.
   c) Discuss the distance travelled by small and large pistons.

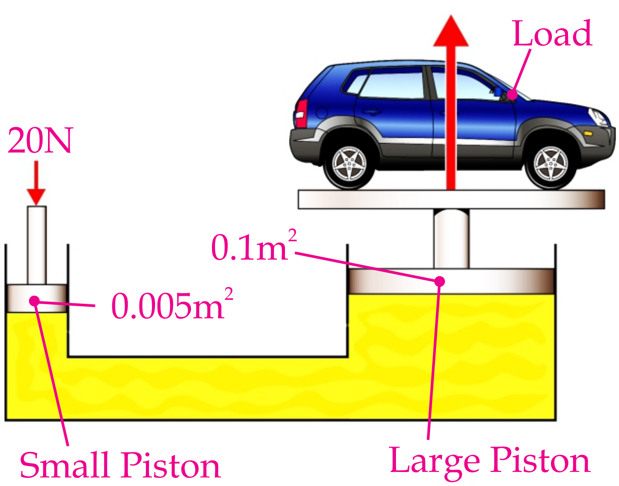


Fig 5.15
A hydraulic system