1.8 Pressure

FOCUS POINTS

★ Define pressure as force per unit area, and illustrate with examples.
★ Describe how pressure varies with depth in a liquid.

★ Calculate the change in pressure beneath the surface of a liquid using the correct equation.

The large flat feet of an Arabian camel prevent it sinking into the soft sand of the desert. This is because the weight of the camel is spread over the area of its four large feet. It appears that the effect of a force depends on the area over which it acts. The effect can be quantified by introducing the concept of pressure. In this topic you will learn that pressure increases as the force increases and the area over which the force acts becomes less. Pressure in a liquid is found to increase with both density and depth. If a deep-sea diver surfaces too quickly, the pressure changes can lead to a condition called the bends. The properties of liquid pressure are utilised in applications ranging from ≈zwater supply systems and dam construction to hydraulic lifts.

Pressure

To make sense of some effects in which a force acts on an object we have to consider not only the force but also the area on which it acts. For example, wearing skis prevents you sinking into soft snow because your weight is spread over a greater area. We say the **pressure** is less.

Pressure is defined as the force per unit area (i.e. $1\,m^2$) and is calculated from

$$\text{pressure} = \frac{\text{force}}{\text{area}}$$

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

Key definition
Pressure the force per unit area

The unit of pressure is the **pascal** (Pa). It equals 1 newton per square metre (N/m^2) and is quite a small pressure. An apple in your hand exerts about 1000 Pa.

The greater the area over which a force acts, the less the pressure. This is why a tractor with wide wheels can move over soft ground. The pressure is large when the area is small and this is why nails are made with sharp points. Walnuts can be broken in the hand by squeezing two together, rather than one alone, because the area of contact is smaller leading to a higher pressure on the shells (Figure 1.8.1).

▲ **Figure 1.8.1** Cracking walnuts by hand

Worked example

Figure 1.8.2 shows the pressure exerted on the floor by the same box standing on end (Figure 1.8.2a) and lying flat (Figure 1.8.2b). If the box has a weight of 24 N, calculate the pressure on the floor when the box is

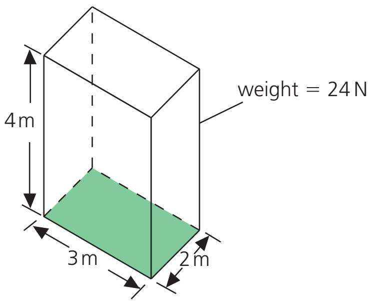
a standing on end as in Figure 1.8.2a
b lying flat as in Figure 1.8.2b.

a area = 3 m × 2 m = 6 m^2

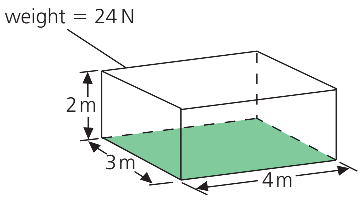
$$\text{pressure} = \frac{\text{force}}{\text{area}} = \frac{24\,\text{N}}{6\,\text{m}^2} = 4\,\text{Pa}$$

b area = 3 m × 4 m = 12 m^2

$$\text{pressure} = \frac{\text{force}}{\text{area}} = \frac{24\,\text{N}}{12\,\text{m}^2} = 2\,\text{Pa}$$



▲ **Figure 1.8.2a**



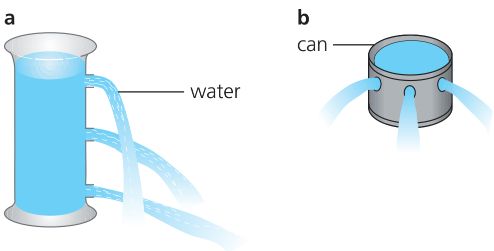
▲ **Figure 1.8.2b**

Now put this into practice

1 A rectangular box has a width of 2 m, a height of 5 m and a depth of 2 m.
  a Calculate the area of
    i the base of the box and
    ii one of the sides of the box.
  b If the box has a weight of 80 N, calculate the pressure on
    i the base of the box
    ii one of the sides of the box.
2 **a** Calculate the pressure on a surface when a force of 50 N acts on an area of
    i 2.0 m^2
    ii 100 m^2
    iii 0.50 m^2.
  b A pressure of 10 Pa acts on an area of 3.0 m^2. What is the force acting on the area?

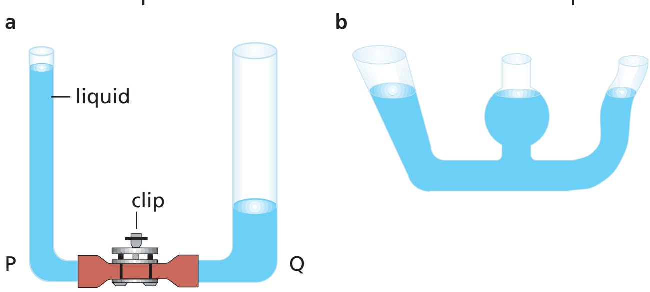
Liquid pressure

1 *Pressure in a liquid increases with depth*. This is because the further down you go, the greater the weight of liquid above. In Figure 1.8.3a water spurts out fastest and furthest from the lowest hole.
2 *Pressure at one depth acts equally in all directions*. The can of water in Figure 1.8.3b has similar holes all round it at the same level. Water comes out equally fast and spurts equally far from each hole. Hence the pressure exerted by the water at this depth is the same in all directions.



▲ **Figure 1.8.3**

3 *A liquid finds its own level*. In the U-tube of Figure 1.8.4a the liquid pressure at the foot of P is greater than at the foot of Q because the left-hand column is higher than the right-hand one. When the clip is opened, the liquid flows from P to Q until the pressure and the levels are the same, i.e. the liquid 'finds its own level'. Although the weight of liquid in Q is now greater than in P, it acts over a greater area because tube Q is wider.
In Figure 1.8.4b the liquid is at the same level in each tube and confirms that the pressure at the foot of a liquid column depends only on the *vertical* depth of the liquid and not on the tube width or shape.



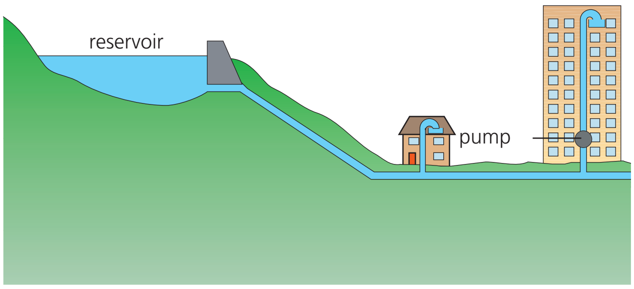
▲ **Figure 1.8.4**

4 *Pressure depends on the density of the liquid.* The denser the liquid, the greater the pressure at any given depth. The densities of some different liquids are listed in Table 1.4.1 in Topic 1.4.

Water supply system

A town's water supply often comes from a reservoir on high ground. Water flows from it through pipes to any tap or storage tank that is below the level of water in the reservoir (Figure 1.8.5). The lower the place supplied, the greater the water pressure. In very tall buildings it may be necessary to pump the water to a large tank in the roof.

Reservoirs for water supply or for hydroelectric power stations are often made in mountainous regions by building a dam at one end of a valley. The dam must be thicker at the bottom than at the top due to the large water pressure at the bottom.



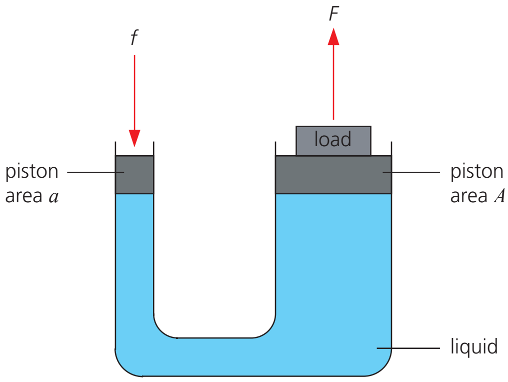
▲ **Figure 1.8.5** Water supply system

Test yourself

1 Why is the pump needed in the high-rise building shown in Figure 1.8.5?
2 Why are dam walls built to be thicker at the bottom than the top?

Hydraulic machines

Liquids are almost incompressible (i.e. their volume cannot be reduced by squeezing) and they 'pass on' any pressure applied to them. Use is made of these facts in hydraulic machines. Figure 1.8.6 shows the principle on which they work.



▲ **Figure 1.8.6** The hydraulic principle

Suppose a downward force f acts on a piston of area a. The pressure transmitted through the liquid is

$$\text{pressure} = \frac{\text{force}}{\text{area}} = \frac{f}{a}$$

This pressure acts on a second piston of larger area A, producing an upward force, $F = \text{pressure} \times \text{area}$:

$$F = \frac{f}{a} \times A$$

or

$$F = f \times \frac{A}{a}$$

Since A is larger than a, F must be larger than f and the hydraulic system is a force multiplier; the **multiplying factor** is A/a.

Worked example

A hydraulic jack is used to lift a heavy load. A force of 1 N is applied to a piston of area 0.01 m^2 and pressure is transmitted through the liquid to a second piston of area of 0.5 m^2. Calculate the load which can be lifted.

Taking $f = 1$ N, $a = 0.01$ m^2 and $A = 0.5$ m^2 then

$$F = f \times \frac{A}{a}$$

so

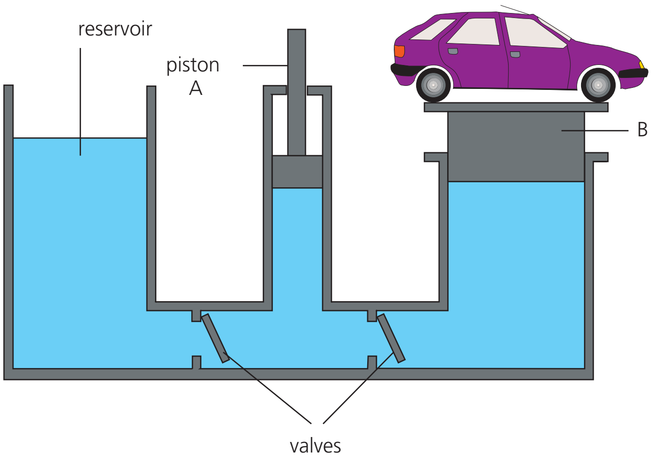
$$F = 1\,\text{N} \times \frac{0.5\,\text{m}^2}{0.01\,\text{m}^2} = 50\,\text{N}$$

A force of 1 N could lift a load of 50 N; the hydraulic system multiplies the force 50 times.

Now put this into practice

1 In a hydraulic jack a force of 20 N is applied to a piston of area 0.1 m^2. Calculate the load which can be lifted by a second piston of area 1.5 m^2.
2 In a hydraulic jack a load of 70 N is required to be lifted on an area of 1.0 m^2. Calculate the force that must be applied to a piston of area 0.1 m^2 to lift the load.
3 Name the property of a liquid on which a hydraulic jack relies.

A **hydraulic jack** (Figure 1.8.7) has a platform on top of piston B and is used in garages to lift cars. Both valves open only to the right and they allow B to be raised a long way when piston A moves up and down repeatedly.

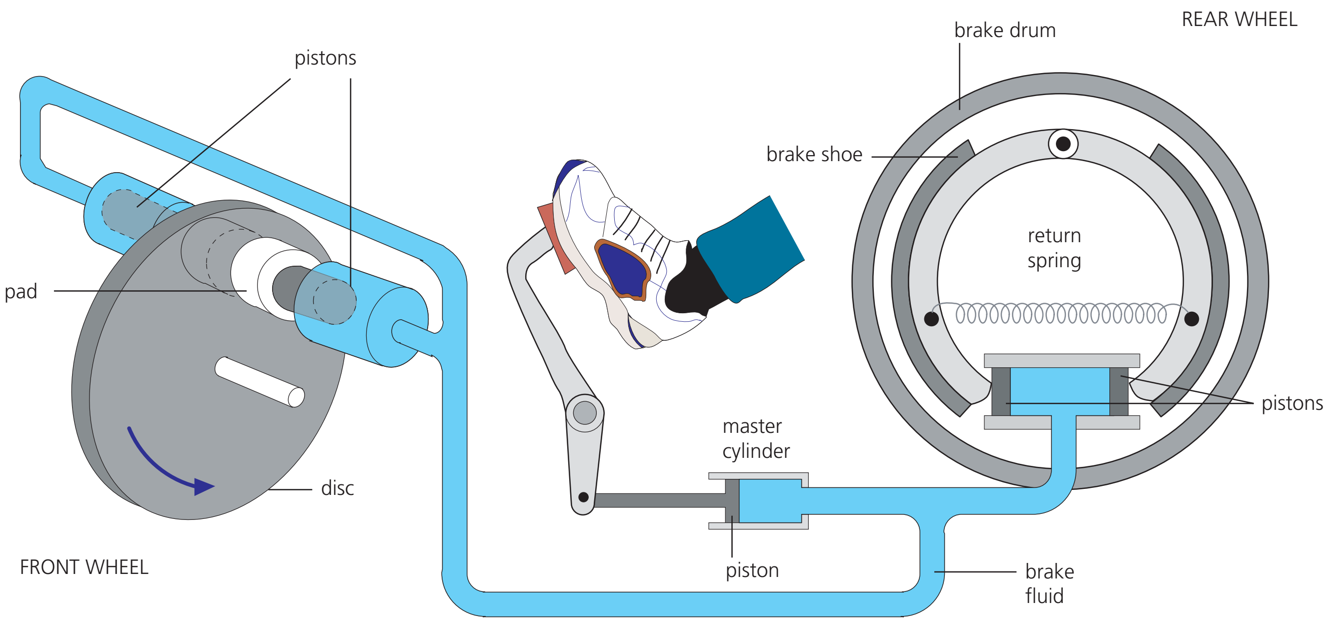


▲ **Figure 1.8.7** A hydraulic jack

Hydraulic fork-lift trucks and similar machines such as loaders (Figure 1.8.8) work in the same way.

▲ **Figure 1.8.8** A hydraulic machine in action

Hydraulic car brakes are shown in Figure 1.8.9. When the brake pedal is pushed, the piston in the master cylinder exerts a force on the brake fluid and the resulting pressure is transmitted equally to eight other pistons (four are shown). These force the brake shoes or pads against the wheels and stop the car.



▲ **Figure 1.8.9** Hydraulic car brakes

Expression for liquid pressure

In designing a dam an engineer has to calculate the pressure at various depths below the water surface. The pressure increases with depth and density.

An expression for the change in pressure Δp at a depth Δh below the surface of a liquid of density ρ can be found by considering a horizontal area A (Figure 1.8.10). The force acting vertically downwards on A equals the weight of a liquid column of height Δh and cross-sectional area A above it. Then

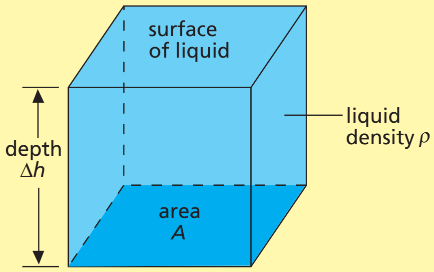
volume of liquid column = ΔhA

Since mass = density × volume, then

mass of liquid column $m = \rho\Delta hA$

weight of liquid column = $mg = \rho\Delta hAg$

$\therefore$ force on area $A = \rho\Delta hAg$



▲ **Figure 1.8.10**

As

$$\text{pressure due to liquid column} = \text{force/area} = g\rho\Delta hA/A$$

we can write

$$\Delta p = \rho g\Delta h$$

where Δp is the change in pressure beneath the surface of the liquid at depth Δh due to the weight of a liquid of density ρ and g is the gravitational field strength.

This pressure acts equally in all directions at depth Δh and depends only on Δh and ρ. Its value will be in Pa if Δh is in m and ρ in kg/m^3.

Test yourself

3 Calculate the increase in pressure at a depth of 2 m below the surface of water of density 1000 kg/m^3.

4 Calculate the depth of water of density 1020 kg/m^3 where the pressure is 3.0×10^6 Pa.

Going further

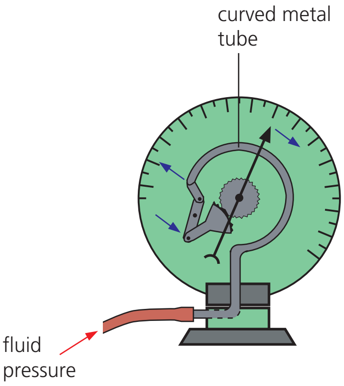
Pressure gauges

These measure the pressure exerted by a fluid, in other words by a liquid or a gas.

Bourdon gauge

This works like the toy shown in Figure 1.8.11, where the harder you blow into the paper tube, the more it uncurls. In a Bourdon gauge (Figure 1.8.12), when a fluid pressure is applied, the curved metal tube tries to straighten out and rotates a pointer over a scale.
Car oil-pressure gauges and the gauges on gas cylinders are of this type.

▲ **Figure 1.8.11**



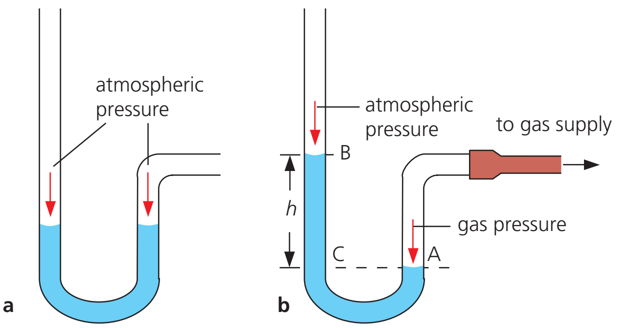
▲ **Figure 1.8.12** A Bourdon gauge

U-tube manometer

In Figure 1.8.13a each surface of the liquid is acted on equally by atmospheric pressure and the levels are the same. If one side is connected to, for example, the gas supply (Figure 1.8.13b), the gas exerts a pressure on surface A and level B rises until

$$\text{pressure of gas} = \text{atmospheric pressure} + \text{pressure due to liquid column BC}$$

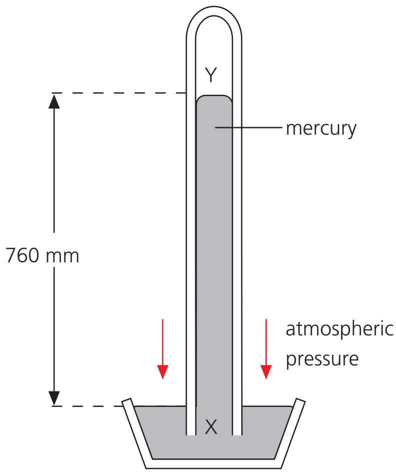
The pressure of the liquid column BC therefore equals the amount by which the gas pressure *exceeds* atmospheric pressure. It equals $h\rho g$ (in Pa) where h is the vertical height of BC (in m) and ρ is the density of the liquid (in kg/m^3). The height h is called the head of liquid and sometimes, instead of stating a pressure in Pa, we say that it is so many cm of water (or mercury for higher pressures).



▲ **Figure 1.8.13** A U-tube manometer

Mercury barometer

A barometer is a manometer which measures atmospheric pressure. A simple barometer is shown in Figure 1.8.14. The pressure at X due to the weight of the column of mercury XY equals the atmospheric pressure on the surface of the mercury in the bowl. The height XY measures the atmospheric pressure in mm of mercury (mmHg).



▲ **Figure 1.8.14** Mercury barometer

The *vertical* height of the column is unchanged if the tube is tilted. Would it be different with a wider tube? The space above the mercury in the tube is a vacuum (except for a little mercury vapour).

Revision checklist

After studying Topic 1.8 you should know and understand:

✓ that the pressure beneath a liquid surface increases with depth and density and that pressure is transmitted through a liquid.

After studying Topic 1.8 you should be able to:

✓ define pressure from the equation $p = F/A$ and give everyday examples of its use; recall the units of pressure

✓ calculate the change in pressure below the surface of a liquid.

Exam-style questions

1 The following statements relate to definitions of pressure. In each case write down if the statement is *true* or *false*.

A Pressure is the force acting on unit area. [1]

B Pressure is calculated from force/area. [1]

C The SI unit of pressure is the pascal (Pa) which equals 1 newton per square metre ($1\,N/m^2$). [1]

D The greater the area over which a force acts, the greater the pressure. [1]

E Force = pressure × area. [1]

F The SI unit of pressure is the pascal (Pa) which equals 1 newton per metre (1 N/m). [1]

[Total: 6]

2 a Calculate the pressure exerted on a wood-block floor by each of the following.

i A box weighing 2000 kN standing on an area of $2\,m^2$. [2]

ii An elephant weighing 200 kN standing on an area of $0.2\,m^2$. [2]

iii A girl of weight 0.5 kN wearing high-heeled shoes standing on an area of $0.0002\,m^2$. [2]

b A wood-block floor can withstand a pressure of 2000 kPa ($2000\,kN/m^2$). State which of the objects in **a** will damage the floor and explain why. [2]

[Total: 8]

3 In a hydraulic press a force of 20 N is applied to a piston of area $0.20\,m^2$. The area of the other piston is $2.0\,m^2$.

a Calculate the pressure transmitted through the liquid. [2]

b Calculate the force on the other piston. [2]

c Explain why a liquid and not a gas is used as the 'fluid' in a hydraulic machine. [1]

d State another property of a liquid on which hydraulic machines depend. [1]

[Total: 6]

4 a The pressure in a liquid varies with depth and density. State whether the following statements are *true* or *false*.

A The pressure in a liquid increases with depth. [1]

B The pressure in a liquid increases with density. [1]

C The pressure in a liquid is greater vertically than horizontally. [1]

b Calculate the increase in pressure at a depth of 100 m below the surface of sea water of density $1150\,kg/m^3$. [4]

[Total: 7]

5 a State the equation which relates the change in pressure in a liquid to the depth below the liquid surface. [2]

b Name the unit of pressure. [1]

c Calculate the depth of water of density $1030\,kg/m^3$ where the pressure is $7.5 \times 10^6\,Pa$. [3]

[Total: 6]

Going further

6 Figure 1.8.15 shows a simple barometer.

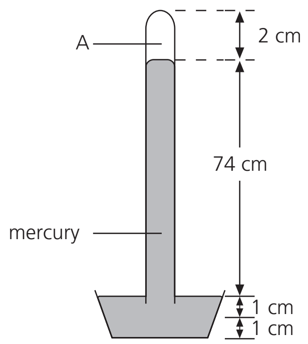
a What is the region A? [1]

b What keeps the mercury in the tube? [1]

c What is the value of the atmospheric pressure being shown by the barometer? [1]

d State what would happen to this reading if the barometer were taken up a high mountain? Give a reason. [2]

[Total: 5]



▲ **Figure 1.8.15**