# CHAPTER 07

# Hydrostatics: The Physics of Fluids

## 7.1 FLUIDS AT REST?

Fluids play a central role in our daily lives. But what are they? We breathe them, we drink them and they flow through our veins. The sea is a fluid; and the atmosphere; and the core of the Earth. In a car, there are fluids in the tyres, the petrol tank, the radiator, the combustion chambers of the engine, the exhaust pipe, the lubrication system and the hydraulic brakes. Medicine, too, relies on an understanding of fluids in action: the pumping of kidney dialysis machines and the anaesthetist using a heart–lung machine, to name just two. The safe movement of fluids is of vital importance to society. Ruptured oil pipelines and blood vessels are reminders of what can happen if the physics of them is neglected. An understanding of the physics of fluids is essential to society.

You probably already know that fluids include liquids and gases — substances that flow. But they are more than just that. In this chapter we will be considering the science of fluids at rest — **hydrostatics**.

Have you ever wondered about these questions concerning fluids:

- Sugar flows out of a packet when I tip it up. Is sugar a fluid?
- Fresh eggs sink in water but stale eggs float. What is happening?
- In England, sandshoes are called 'plimsolls'. Why is this and who was Plimsoll?
- Why is quicksand so deadly? Why can't you get out?
- Could you walk across a tub of mercury? How far down would you sink?
- Why do some scuba divers die when they come up to the surface too fast?
- Car brake fluid strips the paint off cars if it is spilt. Why don't they use water or oil?
- If a doctor said your blood pressure was '120 over 80' would you care?
- Unwanted pets are sometimes killed by 'decompression'. It sounds cruel — is it?

**NOVEL CHALLENGE**

Long ago people predicted high and low tides based on observed regularities, but they didn't have a theory of tides. Was this science?

### What is a fluid?

A **fluid** is a substance that can flow. Gases and liquids can flow — solids can't. Fluids take on the shape of any container in which they are put. Some materials such as pitch take a long time to flow, but eventually they do, so we call them fluids. Glass in medieval windows is now thicker at the bottom than at the top because it has slumped a bit. Glass too is a fluid, although a very **viscous** (thick) one. 'Viscous' comes from the Latin *viscum* meaning 'birdlime'. This was a sticky gum applied to branches to trap bird pests in orchards. Of liquids, the least viscous is liquid helium (–270°C), which is so mobile that it creeps up and over the sides of its container.

But maybe everything will flow eventually so maybe everything is a fluid! What's the point of distinguishing between fluids and solids? The point is: no, not everything is a fluid. Ice isn't, steel isn't, bricks aren't. A fluid is a system of particles loosely held together by their own attractive forces or by the restraining forces exerted by the walls of the container. A fluid

**Photo 7.1**
Pitch drop experiment. Professor John Mainstone of the Department of Physics at the University of Queensland, with the current pitch drop about two years after the previous drop.

will flow even if the forces are very weak. A solid will not flow at all unless the applied forces are in excess of some threshold value. Pitch and glass are fluids of high viscosity. Even if the force is small they will flow, although very slowly. (See photo of pitch drop experiment on previous page.) However, in practical and useful terms, we can think of fluids as being substances that can be pumped along pipes.

## PRESSURE 7.2

When a fluid is placed into a container it exerts a force on any surface exposed to it. The magnitude of this force divided by the area over which the force acts is called **pressure**.

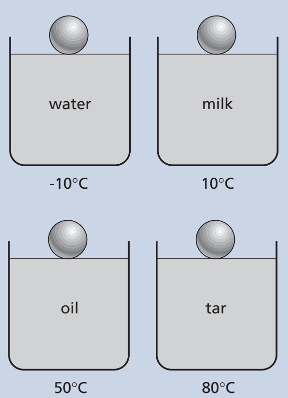
$$\text{Pressure} = \frac{\text{force}}{\text{area}} \qquad P = \frac{F}{A}$$

**NOVEL CHALLENGE**

In setting the world record for a bed of nails, a 60 kg man lay down on 259 nail points in a 30 × 45 cm board. The contact area for each nail with his skin was 10 $mm^2$. Then a 268 kg weight was placed on top of him. Calculate the pressure of the nails on his skin.

**NOVEL CHALLENGE**

*Which of the following ball bearings will fall most slowly?*




**NOVEL CHALLENGE**

You can exert a force of 250 N with your incisor teeth and 1220 N with your molars. *Which do you estimate to produce the higher pressure?* Note: *your front incisors are about 8 mm × 0.2 mm and your molars are about 8 mm × 8 mm.*

If the force is in newtons (N) and the area in square metres ($m^2$), the pressure is in **pascals** (Pa). One pascal equals one newton per square metre. Although pressure is defined in terms of a vector quantity, it is not a vector quantity itself. The unit *pascal* was named after the French scientist and mathematician **Blaise Pascal** (1623–62). Pascal suffered from a condition known as a soft fontanelle, in which the cartilage between the bones of the skull never properly hardened. This gave rise to migraine headaches so severe that it halted his scientific thinking. Nevertheless he made huge contributions to science and philosophy during his 39 years on Earth. Although to physicists he is best remembered for his work on pressure, in general he is remembered for his remarkable insights in religious thinking, fragments of which are recorded in his book *Pensées*. A computer language has since been named in his honour.

### NEI Activity 7.1 HIGH PRESSURE

The *Guinness Book of Records* lists the highest atmospheric pressure ever recorded on Earth as 108.38 kPa in Siberia in 1968. Where was the lowest recorded; what was it and when?

### Table 7.1 SOME PRESSURES

| | PRESSURE (Pa) |
|---|---|
| Centre of the Sun | $2 \times 10^{16}$ |
| Centre of the Earth | $4 \times 10^{11}$ |
| Highest sustained laboratory pressure | $2 \times 10^{10}$ |
| Deepest ocean trench | $1 \times 10^{10}$ |
| Spike heels on dance floor | $1 \times 10^{6}$ |
| Car tyre | $3 \times 10^{5}$ |
| Atmosphere at sea level | $1 \times 10^{3}$ |
| Blood pressure | $2 \times 10^{4}$ |
| Loudest tolerable sound | 30 |
| Faintest detectable sound | $3 \times 10^{-5}$ |
| Best laboratory vacuum | $1 \times 10^{-12}$ |

### Example

A person has a mass of 65 kg. The contact area between his shoes and the floor is 315 $cm^2$. Calculate the pressure he exerts on the floor.

### Solution

Force (weight) = $mg$ = 650 N; area = 315 cm$^2$ = $\frac{315}{100 \times 100}$ m$^2$ = 0.0315 m$^2$.

$$P = \frac{F}{A} = \frac{650}{0.0315} = 20\ 600 \text{ Pa}$$

You can have a high pressure without a large force. A chisel (Figure 7.1) has a sharp tip and when a small force is applied it will easily penetrate wood (and your shoe if you drop it). A small force of 1 newton applied to the handle will be transferred to the point and produce a very large pressure. If the point has an area of $10^{-6}$ m$^2$, the pressure will be:

$$P = \frac{F}{A} = \frac{1}{10^{-6}} = 10^6 \text{ Pa (1 megapascal)}$$

Because many surfaces cannot stand this pressure, the chisel will penetrate them. Hardwood or pine are good examples.

This concept helps us to understand the action of knives, needles and nails. They work because of the small contact area. On the other hand, army tanks and bulldozers work on the reverse principle — the bigger the surface area of their caterpillar treads, the less likely they are to sink into muddy ground. Four-wheel drive owners will know that this technique can be applied when driving in loose sand on a beach. Tyres can be deflated to half normal pressure to increase the surface area and hence lessen the amount they sink into the sand (Figure 7.2).

**NOVEL CHALLENGE**

The pressure in an aeroplane's tyre was measured with a pressure gauge at sea level. The plane flew off and landed on a high mountain airstrip. If the temperature was the same as at sea level, how would the pressure gauge reading compare with that at sea level?

**Figure 7.1**

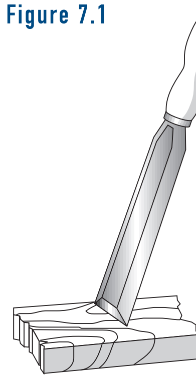
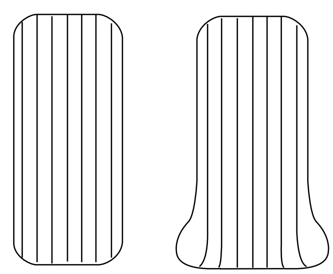


**Figure 7.2**
In soft sand it often helps to deflate the tyres to about half the normal pressure.

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## Activity 7.2 ROADS AND TYRES

Roads gradually break up from the constant pressure of passing car and truck tyres. But big trucks are not always the worst offenders as their load is often spread over eighteen or more tyres.

### Part A

- Use a ruler to measure the contact area of a bicycle tyre with a flat surface while a person is sitting on the bike. Measure or estimate the total mass of the bike plus rider and calculate the pressure exerted by the tyres on the surface. Assume that half the weight is supported by each tyre.
- Repeat for a car. The mass of the car will be in the owner's handbook. Most cars are between 1000 kg and 2000 kg.

### Part B

Rank the following in order of the pressure exerted by the tyres on the road. Include the two results from above.

- A BMX bicycle; mass 20 kg plus rider 45 kg; contact area 10 cm × 5 cm per tyre.
- A Porsche 911 Carerra, mass 1370 kg, on four tyres, each with a contact area of 15 cm × 20 cm.
- A Landcruiser, mass 2960 kg, on four tyres, each with a contact area of 17 cm × 22 cm.
- A fully laden semi-trailer of mass 42 t; 22 tyres, each with a contact area of 20 cm × 20 cm.

**NOVEL CHALLENGE**

Four car tyres are inflated to the same pressure. One wheel is jacked up.
*How does this change the pressure in the jacked-up tyre and in the other three?*

## Questions

1 A girl with a weight of 500 N stands in snow on a pair of skis. Each ski has a contact area of 1.5 m × 0.13 m. Calculate the pressure on the snow.

2 Calculate the pressure at the bottom of a round swimming pool of diameter 6.0 m filled to a depth of 1.2 m.

3 In some shops and factories, cheese is cut by a wire. Imagine a steel wire with a diameter of 0.2 mm being pulled through a block of cheese 20 cm wide by the downward force of a 5 kg mass (50 N). Calculate the pressure acting on the cheese.

# MEASURING PRESSURE 7.3

## Atmospheric pressure

The gas particles of the atmosphere have weight and they exert a pressure on us and the surface of the Earth. It can be calculated that about 150 t of air pushes down on just the floor of a living room. This is the atmospheric pressure and has a value of 101 325 pascal (Pa) or 101.325 kPa. The higher you go up into the atmosphere the smaller the amount of air above you and hence the lower the pressure.

**Table 7.2 CHANGES IN ATMOSPHERIC PRESSURE**

| ALTITUDE (m) | PRESSURE (kPa) |
|---|---|
| 15 000 | 12.0 |
| 11 000 | 22.5 |
| 9 000 | 31.0 |
| 6 000 | 47.1 |
| 3 000 | 70.0 |
| 0 (sea level) | 101.3 |

Concrete floors are able to stand very high pressures. Concrete is extremely resistant to compression forces but relatively weak to stretching forces. Concrete batching plants can supply different mixes of concrete depending on its purpose. Household concrete slabs typically use a 20 megapascal (20 MPa) blend, whereas high-rise columns need 80 MPa concrete.

### NEI Activity 7.3 CONCRETE STRENGTH TESTING (CST)

1 Find out the procedure for testing the strength of concrete made by the ready-mix batching plants. They only sample one in 20 truckloads. Why? What do they do with the concrete samples after testing?

2 Find out the specifications (in MPa) for several types of concrete available from the batching plant. What makes them different? Are they sold by the tonne or cubic metre? Does their cost vary?

3 Reinforced concrete and pre-stressed concrete both have steel bars or cables inside them. Why is this?

4 Testing laboratories express the strength of concrete in kilonewtons per square millimetre. How is this related to megapascals?

**NOVEL CHALLENGE**

A fluorescent light tube is stood upright in a bucket of water and a small hole is cut in the tube underwater with a triangular file. The gas pressure inside the tube is 330 Pa. To what height do you estimate the water will rise? Try it but first think of how you will dispose of the water-filled tube.

**NOVEL CHALLENGE**

An empty soft-drink can has some water in it and is boiled over a Bunsen burner. It is quickly inverted and stood up in a tray of cool water. *What do you predict will happen? Try it, but use tongs.*

**NOVEL CHALLENGE**

A piece of burning paper is placed in a conical flask and a boiled egg placed in the top. You can imagine what happens. But how to reverse the process without touching the egg — now that's where the physics is needed.

## Measuring air pressure

Three common ways of measuring air pressure are with the **barometer**, the **manometer** and the **Bourdon gauge**.

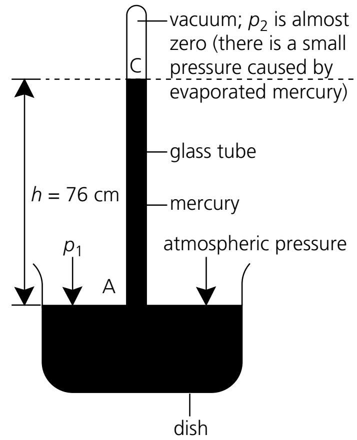
The barometer is used to measure atmospheric pressure. The word is derived from the Greek *baros* meaning 'weight' and hence refers to the weight of the atmosphere. The manometer also measures pressure, not of the atmosphere but of some other gas relative to atmospheric pressure. In Greek, *manos* means 'rare', referring to gases at low pressure where the particles are few and far between.

## The barometer

The invention of the mercury barometer (1643) by Evangelista Torricelli arose from his realisation that air has weight. He noted that if the open end of a glass tube filled with mercury is inverted in a bowl of mercury, the atmospheric pressure ($p_1$) on the bowl of mercury will affect the height of the column of mercury in the glass tube. The greater the air pressure, the longer is the mercury column. Normal atmospheric pressure will support a column of mercury 760 mm high. The symbol for mercury, Hg, is from the Greek *hydro-argentum* meaning 'silvery water'. Hence normal atmospheric pressure can be written as 760 mmHg. (See Figure 7.3.)

Mercury is ideal for a liquid barometer, since its high density permits a short column, whereas a water barometer would be 10 m tall at normal atmospheric pressure.

**Figure 7.3**
The mercury barometer.




## The aneroid barometer (Bourdon gauge)

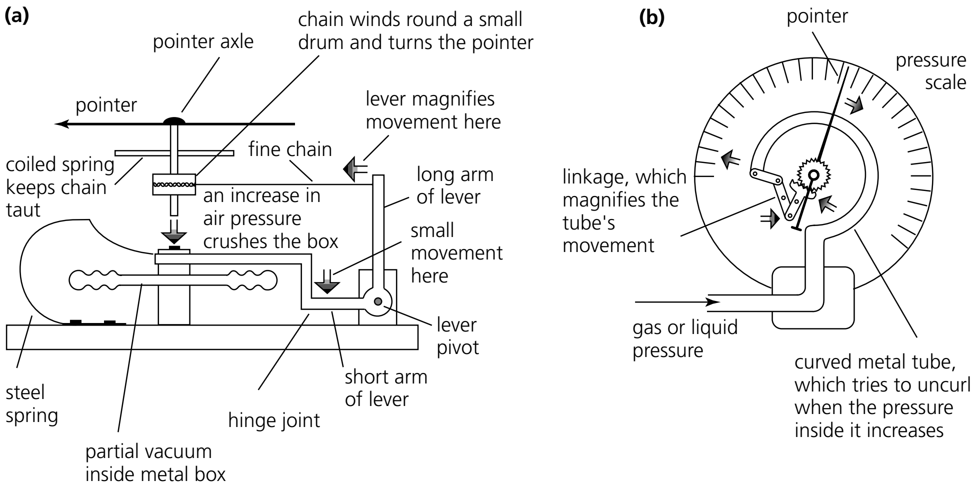
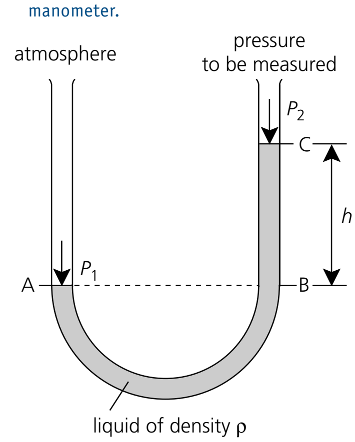



**Figure 7.4**
When the gas pressure inside the curved metal tube increases, the tube tries to uncurl. The end of the tube is linked to a pointer, which reads pressure on a circular scale.
**(a)** The aneroid barometer.
**(b)** The Bourdon gauge.

Most barometers are of the aneroid type and function without liquid. The aneroid barometer, dating from 1843, consists of a small metal box, almost totally evacuated of air. One side is immovable, and the opposite side is connected to a strong spring to keep the box from collapsing. The movable side will expand if the air pressure decreases and will compress if the air pressure increases. The position of the movable side is indicated by a pointer. An aneroid barometer is checked regularly against a mercury barometer for **calibration**.

The aneroid barometer can be easily converted into a barograph, or recording barometer, by adding a pen to the pointer. The ink in the pen describes a trace (**barogram**) on the paper wrapped around a cylinder. The cylinder usually rotates once a day or once a week. Whereas the mercury barometer is used in research laboratories and in important weather stations, aneroid barometers are used in the home, on board ships, and in most weather stations.

**Figure 7.5**
Measuring pressure with a U-tube manometer.




## The manometer

The manometer is the most direct and accurate instrument for measuring liquid and gas pressures of moderate range in the laboratory or in industry. In its common form, known as the U-tube manometer, a tube is partially filled with a liquid such as mercury, oil, or water. With one open end exposed to the atmosphere and the other end to the pressure or vacuum source to be measured, the pressure is determined by noting the difference in level of the liquid in the tube branches. Typically, the reading is in millimetres of mercury (mmHg). A manometer

**Photo 7.2**
A doctor using a sphygmomanometer.

measures the difference between atmospheric pressure and the pressure in a connected vessel. The reading is not the absolute pressure but the **gauge pressure**. Car tyres, for instance, are inflated to about 200 kPa above atmospheric pressure. Their absolute pressure would then be 300 kPa (100 kPa for the atmosphere and 200 kPa for the extra in the tyres) but a tyre pressure gauge only registers 'gauge pressure' over and above atmospheric pressure. Pressure cookers have gauges that register in the same way.

## Blood pressure

Blood pressure is measured with an instrument called a **sphygmomanometer** (Greek *sphygmo* = 'pulse'). It consists of an inflatable cuff, which is wrapped around a patient's arm, and is connected to an open-tube mercury manometer. To take the pressure, a stethoscope is placed over the arteries of the arm just below the cuff and the pulsations of blood in the arteries can be heard. As air is pumped into the cuff, it cuts off the flow of blood, and the sounds stop. Then air is slowly let out of the cuff. When the pressure of the cuff becomes less than the blood pressure, the blood flow returns. The pressure at which the flow of blood starts up again is called the **systolic** pressure, which can be read off the manometer. As more air is let out of the cuff, the sounds become muffled. The pressure at this point is called the **diastolic** pressure.

Blood pressure is expressed as systolic pressure over diastolic pressure. The systolic blood pressure is recorded during the instant that the heart contracts (systole) to force blood into the circulation; it is always higher than the diastolic blood pressure, which is recorded when the heart relaxes between beats (diastole). Thus, blood pressure of 120/80 mmHg means that the systolic (maximum) pressure is 120 and the diastolic (minimum) pressure is 80 mmHg. Readings above 140/90 are usually regarded as high (hypertension). As you get older your normal blood pressure usually gets higher anyway.

Modern electronic sphygmomanometers use a microphone to detect the pulse sound and a pressure sensitive resistor (a strain gauge) to measure the force. However, they need calibration against a mercury sphygmomanometer, which is simple and very reliable.

**NOVEL CHALLENGE**

The sphygmomanometer was invented by René Laënnec in 1816. He used a rolled-up tube of paper to listen to a very fat patient.

*Why isn't the cuff wrapped around the lower part of your arm? Why wouldn't you measure the pressure in that big artery in your neck?*

### EI Activity 7.4 BLOOD PRESSURE

There is probably a sphygmomanometer in your school, possibly in the biology lab. If you have access to it, take your own blood pressure. If you can borrow a stethoscope, listen to the blood flow and see if you can identify the Korotkoff sound. If you are concerned about your blood pressure you should visit your doctor to have it measured properly.

# PASCAL'S PRINCIPLE 7.4

If you squeeze an inflated balloon a bulge pops out somewhere else on the balloon. The increased pressure that you apply is transmitted to the rest of the gas inside the balloon. French scientist Blaise Pascal formulated a principle — **Pascal's principle**:

> Pressure applied at any point to a fluid in a closed vessel is transmitted equally to every other point in the fluid.

Gases can be compressed because the distances between particles are very large compared with the size of the particles themselves. With a liquid, however, the particles are held closely together by a variety of attractive forces including dispersion forces, dipole–dipole forces and hydrogen bonding. Because the particles are in close contact they can't be compressed. If you study chemistry, these forces will be described in detail.

## Pascal's principle in real life

Many devices in common use rely on Pascal's principle. The hydraulic car jack, the hydraulic hoist in a car workshop, the hydraulic brakes in a car and the hydraulic press used to form sheet metal parts are all examples. The word **hydraulic** is made up of *hydra* meaning 'water' and *aulos* meaning 'a pipe'.

Figure 7.6 shows how hydraulic brakes in a car work. When foot pressure is applied to the brake pedal, a small piston is made to move inside a cylinder (the master cylinder). This piston pushes an oily brake fluid along a steel tube to another cylinder (the slave cylinder), which is located on the wheel axle. The fluid pressure moves a piston, which pushes on the brake callipers, forcing a brake pad to press against a brake disk. With drum brakes, the slave cylinder pushes brake shoes against the drum. In the past, hydraulic fluid was made from castor oil and alcohol, but the demands of modern cars on their braking systems are a lot higher than they used to be. A lot of heat is generated by brake friction so a liquid with a high boiling point is needed. For example, high speed pursuits by the London police generated brake fluid temperatures of 188°C, which was sufficient to boil normal brake fluid so a blend of synthetic polymers (glycol ethers and borate esters), corrosion inhibitors and fluid modifiers, with a boiling point of about 280°C, was developed. Any vapour that forms in the hydraulic brake line will make the brakes feel 'spongy' and render them ineffective. Brake fluid has to be 'bled' out of the line to remove any vapour bubbles if this happens. Brake fluids absorb moisture and if the moisture content reaches 1.5%, the boiling point will be about 155°C, the minimum allowed for safe driving. One drawback of modern brake fluid is that it can make a mess of paintwork but this is a small price to pay for a safe braking system. In other hydraulic systems on trucks, graders and bulldozers, a light oil can be used because no heat is generated.

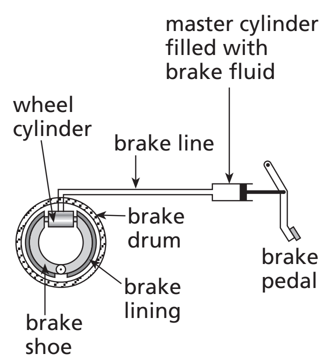



**Figure 7.6**
Hydraulic brake system for a car with drum brakes.

Pascal's principle is also the basis of the hydraulic hoist in a motor garage. An external force (usually a motor) forces a small piston downward. The force is transmitted by an incompressible liquid, in this case water with some soluble oil included as a lubricant, to a larger piston as shown in Figure 7.7. A small input force moving through a large distance equals a large output force moving through a small distance.

In the next chapter you will see that the product of force × distance is called work ($W = \boldsymbol{F}s$). The product of $\boldsymbol{F} \times s$ on input equals the product of $\boldsymbol{F} \times s$ on output. In motor garages, a hydraulic hoist is used to lift a car up high so that it can be worked on from underneath.

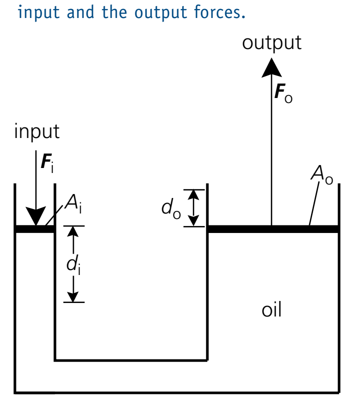



**Figure 7.7**
A hydraulic hoist, used to magnify force $\boldsymbol{F}_i$. The work done by this force, however, is not magnified and it is the same for both the input and the output forces.

In terms of Pascal's principle the relationship can be written:

> Pressure in small cylinder = pressure in large cylinder
> $$P = \frac{F_1}{A_1} = \frac{F_2}{A_2}$$

Thus if a force of 20 N was applied to a piston of diameter 1 cm, it would produce a force of 20 000 N on a piston 30 cm in diameter. This force would lift 2000 kg — that of a car.

### Example

The input piston in a hydraulic hoist has a diameter of 1.50 cm, whereas the output piston is much larger at 25.0 cm. The output piston has to lift a total weight of 30 500 N. Calculate **(a)** the pressure that has to be applied; **(b)** the force needed on the small piston; **(c)** the distance the input piston will move if the output piston moves 1.50 m.

### Solution

**(a)** $P = \frac{\boldsymbol{F}_2}{A_2} = \frac{30\,500}{\pi \times 0.125^2} = 621\,340$ Pa.

**(b)** $\frac{\boldsymbol{F}_1}{A_1} = \frac{\boldsymbol{F}_2}{A_2}$; $\boldsymbol{F}_1 = \frac{\boldsymbol{F}_2 \times A_1}{A_2} = \frac{30\,500 \times p \times 0.0075^2}{p \times 0.125^2} = 110$ N.

**(c)** $\boldsymbol{F}_1 \times s_1 = \boldsymbol{F}_2 \times s_2$; $s_1 = \frac{\boldsymbol{F}_2 \times s_2}{\boldsymbol{F}_1} = \frac{30\,500 \times 1.50}{110} = 4.15$ m.

## Questions

4 A hydraulic hoist in a truck workshop has to be able to lift 85 000 N. The small piston has a diameter of 5.5 cm, whereas the output piston has a diameter of 45.0 cm. Calculate **(a)** the force needed on the small piston; **(b)** the pressure that has to be applied; **(c)** the distance the input piston will move if the output piston moves 1.80 m.

# ARCHIMEDES' PRINCIPLE 7.5

**Archimedes' principle** is the fundamental natural law of buoyancy, first identified by the Greek mathematician and inventor Archimedes in the third century BC. He was once asked by King Hieron II to work out if a gold crown being given to the King was pure gold or if it contained impurities of silver and copper. The story is told that he was sitting in a bath and noticed that objects underwater seemed lighter in weight than they did in air. On realising this he is said to have run naked around the streets of Syracuse shouting '*Eureka*', which translated from the Greek is 'I have found it'.

**NOVEL CHALLENGE**

I was in the swimming pool holding a steel spanner and I thought the spanner should feel lighter because of the buoyant upthrust. But it felt **heavier**. To my hand it really felt heavier. *By why? It slowly dawned on me!*

Most of the story is fiction but he did discover some facts about floating and sinking. Incidentally, Archimedes worked out a way to tell if the crown was pure gold, as you'll see later. He also did some experiments and found that the volume of water that overflowed from a filled container of water was equal to the volume of the object placed in it. It seems commonsense to say that, but you should remember that experimental science was in its infancy 2000 years ago. Archimedes later showed that the **upthrust** (upward force) on an object equals the weight of water displaced. This is Archimedes' principle. It states:

> When an object is wholly or partially immersed in a fluid, the upthrust on the object is equal to the weight of the fluid displaced.

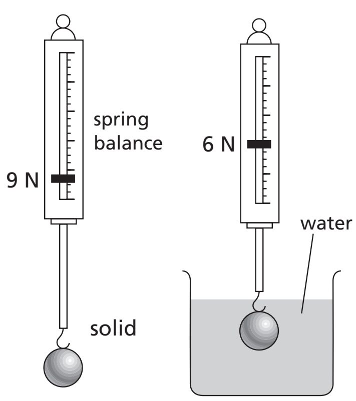
For instance, you probably know that things feel lighter in water than in air. The loss in weight of an object (the upthrust) is equal to the weight of water that it has displaced. If it is fully submerged the volume of water displaced is the same as the volume of the object. The weight of this volume of water is equal to the upthrust.

In general:

> Weight in air – apparent weight (in the fluid) = upthrust

The weight of an object in the fluid is better called the 'apparent' weight (or 'scale reading').

**Figure 7.8**
When a heavy object is placed in water, it experiences an upthrust. In this case the upthrust is 3 N.




### Example

A housebrick has a volume of 1900 cm$^3$ and a weight in air of 80 N. What is its apparent weight in water? The density of water is 1.00 g cm$^{-3}$.

### Solution

- Volume of water displaced = volume of brick = 1900 cm$^3$.
- Mass of water displaced = density × volume = 1.00 × 1900 = 1900 g = 1.9 kg.
- Weight of water displaced = mg = 1.9 × 10 = 19 N.
- Weight in water (apparent weight) = weight in air – upthrust = 80 N – 19 N = 61 N.

*Note:* some people prefer to use the units *kg m*$^{-3}$ for density. While this is the correct usage of SI units, *g cm*$^{-3}$ is commonly used. The conversion is: 1 g cm$^{-3}$ = 1000 kg m$^{-3}$.

## Specific gravity

A litre of water has a mass of 1.00 kg, but the same volume of methylated spirits has a mass of only 0.79 kg. We can say that the density of methylated spirits is 0.79 that of water. This is called its **relative density (RD)** or its **specific gravity (SG)**. The two terms are interchangeable and although relative density is more correct, specific gravity is widely used in industry and the other sciences.

The specific gravity (SG) is defined as the ratio of the mass of an object in air compared with the mass of an equal volume of water.

$$\text{Specific gravity} = \frac{\text{mass of object in air}}{\text{mass of equal volume of water}}$$

But it can also be written:

$$\text{specific gravity} = \frac{\text{weight of object in air}}{\text{weight of equal volume of water}}$$

According to Archimedes' principle, the weight of an equal volume of water equals the upthrust (weight loss) when it is submerged. Thus:

$$\text{specific gravity} = \frac{\text{weight in air}}{\text{weight loss when submerged in water}}$$

or

$$\text{specific gravity} = \frac{\text{weight in air}}{\text{weight in air} - \text{apparent weight in water}}$$

$$\text{SG} = \frac{W_A}{W_A - W_W}$$

In the example above, this equation gives a value of 80/19 = 4.2 g cm$^{-3}$. This value can be confirmed by dividing the mass of 8 kg (= 8000 g) by a volume of 1900 cm$^3$, which also equals 4.2 g cm$^{-3}$.

### Example

A crown supposedly made of gold weighs 8.00 N in air. If the SG of gold is 19.3, what should be the crown's apparent weight in water?

### Solution

$$\text{SG} = \frac{\text{weight in air}}{\text{weight loss when submerged in water}}$$

$$\text{weight loss} = \frac{\text{weight in air}}{\text{specific gravity}} = \frac{8.00}{19.3} = 0.415$$

The crown's apparent weight should be 8.00 N – 0.415 N = 7.59 N.

## EI Activity 7.5 SPECIFIC GRAVITY OF IRREGULAR OBJECTS

1. Tie a piece of cotton thread around a rock and suspend it from a spring balance. Note the scale reading of the rock in air and again when the rock is fully submerged in water. Calculate the SG.
2. Try it with an iron bolt. Did you get an SG of 7.8?

## Questions

5. When the brass cannons from the wrecked eighteenth century Dutch trading ship *Batavia* were recovered off the West Australian coast in 1988, they found that the cannons had a mass of 1100 kg when lifted out of the water. If the density of brass is 8400 kg m$^{-3}$, what would their apparent weight have been in the water?
6. About 800 iron cannonballs were recovered from the *Batavia*. If each ball had a diameter of 13 cm, calculate **(a)** their mass in air; **(b)** their weight in air; **(c)** their weight in water. The density of iron is 7.8 g cm$^{-3}$ (7800 kg m$^{-3}$).

### NOVEL CHALLENGE

Density of some fluids (in g cm$^{-3}$)

| | |
|---|---|
| Petrol | 0.68 |
| Alcohol | 0.81 |
| Water | 1.00 |
| Sea water | 1.03 |
| Sugar syrup 40% | 1.15 |
| Mercury | 13.6 |

*1 What would have the greater density: **(a)** low-alcohol beer or normal beer; **(b)** Coke or Diet Coke?*

*2 Cans of Coke and Diet Coke were put in a tub of water. Will they both float, sink or one float, one sink? Try it.*

### NOVEL CHALLENGE

A cube of brass measuring 2 cm along its side was placed in a measuring cylinder containing 50 mL of water.

*What volume would the measuring cylinder read now? Another cube with a side twice as big was also added. What would the final volume read?*

# FLOATING AND SINKING 7.6

Fresh eggs sink in water but stale eggs float. Why is that? Fresh eggs are more dense than water — that explains them. But in stale eggs, some of the contents have diffused through the shell and been replaced by air — and they float. They become less dense than water.

So not everything sinks in water. Wood floats, ice floats, polythene floats and so do stale eggs. Archimedes' principle still applies but the volume of water displaced will not be equal to the total volume of the object.

Imagine a 1000 $cm^3$ block of wood floating in water so that four-fifths of its volume is underwater. Thus, the volume of water displaced equals 800 $cm^3$ and this has a mass of 800 g or a weight of 8 N. Hence, by Archimedes' principle, the upthrust must also equal 8 N. As the block is floating, the weight of the block must also equal 8 N. As this is equivalent to a mass of 800 g, the density of the wood can be calculated:

$$\text{Density } (\rho) = \frac{m}{V} = \frac{800}{1000} = 0.8 \text{ g cm}^{-3}$$

*Note:*

The density of a solid floating in a fluid is equal to the density of the fluid times the fraction of the volume submerged.
Density of object = density of fluid × fraction submerged

For regular solids, the fraction submerged can be calculated from measurement of the vertical height under and above the fluid.

### Example 1

A cube of polythene floats with seven-eighths of its volume below the water level. Calculate the density of the polythene.

### Solution

$$\text{Density of object} = \text{density of fluid} \times \text{fraction submerged} = 1.00 \times \frac{7}{8} = 0.875 \text{ g cm}^{-3}$$

### Example 2

A 21 cm long polypropylene drinking straw floats upright in a bottle of water with 2.8 cm of its length above the surface. Calculate the density of polypropylene.

### Solution

$$\text{Density of object} = \text{density of fluid} \times \text{fraction submerged}$$
$$= 1.00 \times \frac{21 - 2.8}{21} = 0.87 \text{ g cm}^{-3}$$

## EI Activity 7.6 DENSITY BY FLOTATION

1 Prepare 10 cm lengths of the following. They should be about 1 cm wide.
- The side of a 2 L plastic milk container (high-density polyethylene); SG 0.95–0.97.
- An icecream bucket (low density polythene); SG 0.91–0.94.
- A plastic drinking straw (polypropylene); SG 0.905.
- A wooden paddlepop stick (pine); SG 0.03–0.04.

**NOVEL CHALLENGE**

The relative density of two types of wood is as follows: ironbark 1.3, balsa 0.24. Balsa is specified as 10 pounds per cubic foot. Is this about right?

**NOVEL CHALLENGE**

One of our students can float up to her earlobe in a swimming pool when floating upright.
**A** Estimate her body density.
**B** How high would she float in seawater (SG 1.030 g $cm^{-3}$)?
**C** Would she float higher or lower in cold water?
**D** Would a boy of the same height and mass float the same way?

**NOVEL CHALLENGE**

The density of salt water is greater than that of fresh water. So, swimming in salt water should be faster as your body floats higher and therefore there is less friction. *True or false, and why?*

2 Float them upright in a filled bottle of water with a narrow neck.
3 Measure the fraction underwater and calculate the density of each.
4 Compare your results with the values given above.
5 How could you estimate what your own density would be in a swimming pool?

## Questions

7 A rubber ball floats with 40% of its volume above water. What is its density?
8 A floating piece of wood displaces 80 $cm^3$ of water. Find the weight and mass of the wood.

## The hydrometer

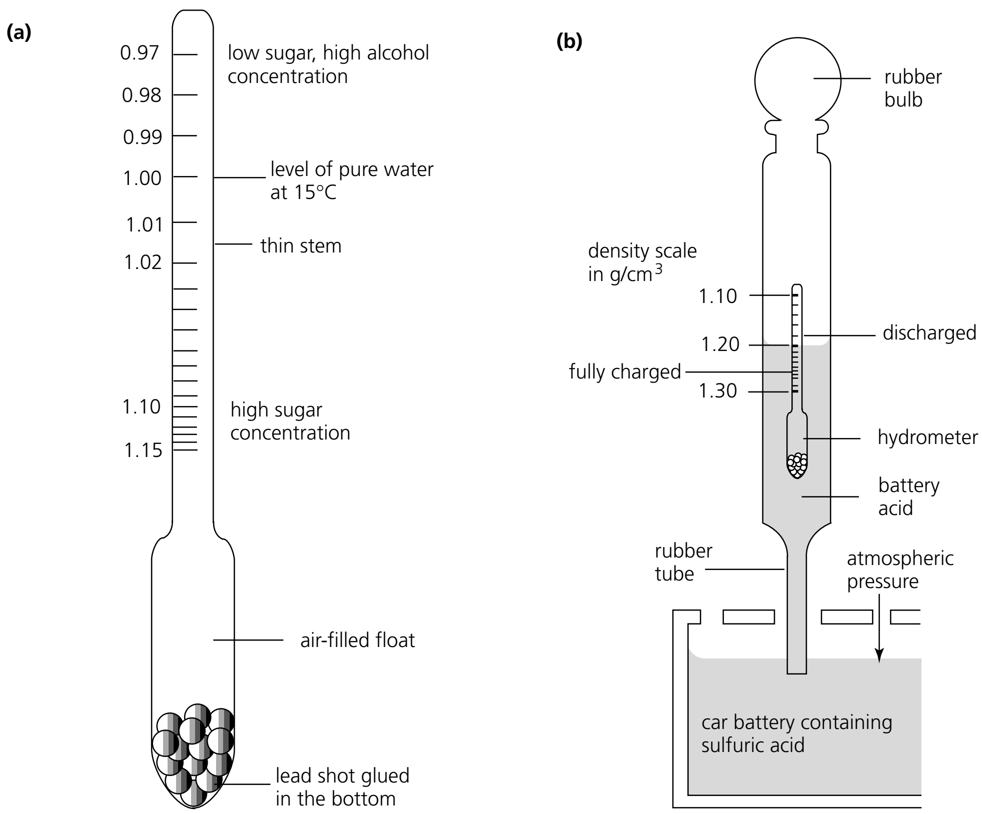



**Figure 7.9**
**(a)** A brewer's hydrometer;
**(b)** A battery acid hydrometer.

**NOVEL CHALLENGE**

A boy is 1.8 m tall and can float upright in pool water with only 5 cm above the water. When he breathes in, his body rises so that it is 25 cm above the surface. Can you estimate the change in density of his body?

**NOVEL CHALLENGE**

Continents float on the liquid mantle of the Earth. Continents have a density of 2800 kg $m^{-3}$ whereas the mantle has a density of 3300 kg $m^{-3}$. If a continent is 35 km thick, prove that the top of the continent is 5.3 km above the mantle surface.

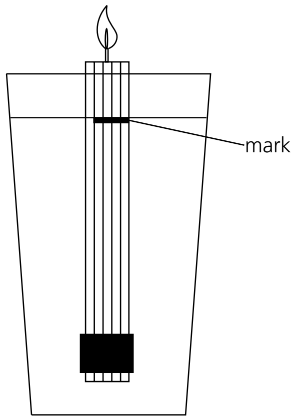
The **hydrometer** is a device for measuring the specific gravity of battery acid, antifreeze solutions, milk, alcohol and other liquids. When industry buys alum solution for water purification the concentration is checked simply by measuring the SG with a hydrometer. The depth to which a graduated glass float sinks in the fluid is proportional to the density of the fluid. The less dense the fluid, the deeper the hydrometer float sinks. The hydrometer for car batteries measures the density of the sulfuric acid in the battery and indicates the state of charge of the battery. A low density indicates that the battery needs recharging.

## Activity 7.7 FLOATING CANDLE

Predict the result of this activity before you attempt it.

1. A candle is weighted at its bottom with some lead or nails taped to it so that it floats upright in water with just a centimetre or two above the surface.
2. Mark the water level on the candle with a pen or a nail (Figure 7.10).
3. Light the candle.
4. As the candle burns, will the mark rise, fall or stay the same in the water?

**Figure 7.10**
A floating candle — will it rise or fall?




## Quicksand — help!

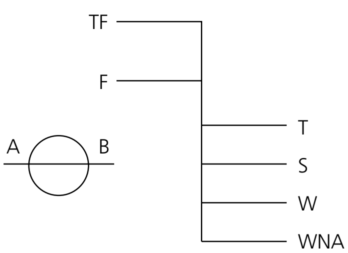
If you fall into quicksand, people say you get sucked under. This is not true — you will float just as in water. But the underground spring feeding it can wander rapidly and often the spring gets diverted a metre or so by your presence so the sand seems to 'set', making it difficult to get out. You won't sink below your armpits but, with your legs trapped, your life expectancy is short. Does anyone have any suggestions?

## The floating of ships

Women in general float higher in water than do men because women (in general, we stress) have more fat on their bodies than men and fat has a lower density than muscle tissue. But not only is the density of the floating object important, but so too is the fluid in which it floats. Ships will float at different levels depending on how salty and how warm (and hence, how dense) the water is. There are special marks on the sides of ships, called the **Plimsoll line** (Figure 7.11), which indicate how deeply a fully laden ship can safely float in water of different types. It was named after Samuel Plimsoll, a member of the British Parliament who introduced the mark in 1885. Until then, ships could be loaded to any level and were seriously overloaded by unscrupulous owners to cut costs. Plimsoll was known as the 'sailor's friend'.

In England, sandshoes with a green line around their sides are called 'plimsolls' after the Plimsoll line.

**Figure 7.11**
The Plimsoll line is now called the international load line. The symbols stand for: T = tropical, S = summer, W = winter, TF = tropical freshwater, WNA = winter north Atlantic. The A and B on the circle stand for the agency that assigned the load line to the ship. In this case it was the American Bureau of Shipping (AB).

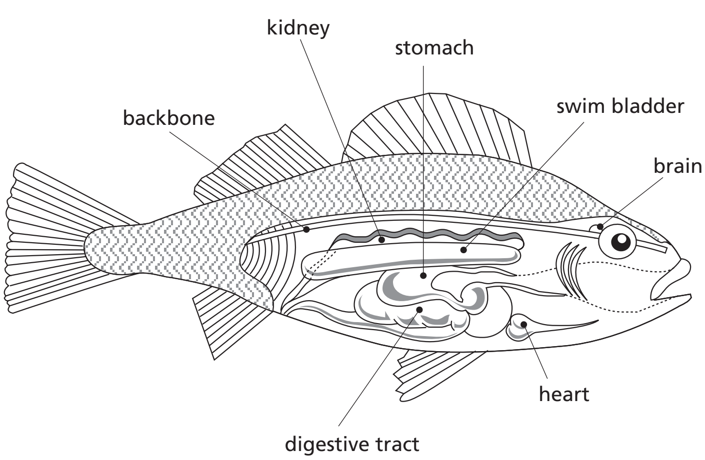



## Fish

Fish have a baglike organ called a swim bladder just below their backbone (Figure 7.12). This provides buoyancy, which enables the fish to remain at a particular depth in the water.

A fish would sink to the bottom if it did not have a way of keeping buoyant. It gains buoyancy by inflating its swim bladder with gases from its blood. But since water pressure increases with depth, a fish's swim bladder would get smaller as it descends and this would reduce its buoyancy. The amount of gas in the bladder must be increased so that the bladder volume is just right to maintain buoyancy. This is done automatically by the fish's nervous system. Sharks and rays do not have a swim bladder. To keep buoyant, these fish must swim constantly. When they rest, they stop swimming and so sink toward the bottom. Many bottom-dwelling bony fish also lack a swim bladder.

**Figure 7.12**
The internal organs of a bony fish.



## Activity 7.8 CARTESIAN DIVER

Fill a 2 L plastic soft drink bottle to about 5 cm from the top with water. Half-fill a test-tube with water and up-end it into the soft drink bottle (Figure 7.13). If the test-tube doesn't float, take it out and remove some of the water. Once you can get it to float upright, screw the cap on the bottle. Squeeze the bottle and watch the 'Cartesian diver'. What happens to the water level inside the test-tube? Can you explain what is going on?

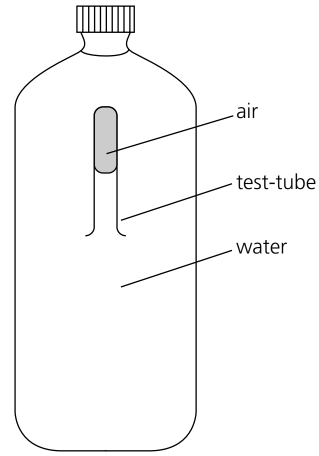



**Figure 7.13**
Cartesian diver — squeeze the bottle and the diver sinks.

## Balloons and blimps

The Montgolfier brothers, Joseph and Jacques, were inventors of the first practical hot-air balloon. They used paper balloons to help English soldiers escape from the Spanish at Gibraltar in 1782, but these caught fire several times. The two Frenchmen were papermakers by trade and discovered in 1782 that smoke from a fire directed into a silk bag made the bag buoyant. In 1783 they gave a public exhibition of their discovery with a balloon that rose to an altitude of about 2 km and stayed aloft for 10 minutes. They later put a sheep, duck, and rooster aboard the balloon to determine the effect of altitude on living creatures.

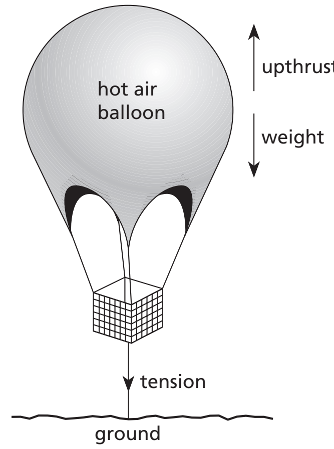
The modern non-rigid blimp has no internal structure to maintain the shape of its hull envelope, which is made of two or three plies of cotton, nylon, or dacron impregnated with rubber for gas tightness (Photo 7.3). Inside the gas space of the hull are two or more air diaphragms called ballonets that are kept under slight pressure, either by blowers or by air that is forced through scoops as a result of the forward motion (ram effect). The ballonets in turn exert pressure on the gas, which fills the envelope, and this pressure in turn serves to stiffen the shape of the envelope and create a smooth flying surface. On take-off the ballonets are almost fully inflated, but as the airship gains altitude and the gas expands, air is bled from the ballonets while a constant pressure is maintained throughout the envelope. When the gas contracts on descent, air is pumped back into the ballonets.

In 1991, Westinghouse Airships launched the 68-m long *Sentinel 1000*, the first in a projected series of blimps to be used by the US Defence Department for a range of surveillance, communications, and patrol duties. The envelope of the *Sentinel 1000* is made of a mix of synthetic fibres that is impervious to weather and almost invisible to radar.

The principles behind the balloon and the blimp are similar to those of objects floating in water. The air is a fluid; it has a density of about 0.0012 g cm$^{-3}$ or 1.2 kg m$^{-3}$. An object such as a balloon displaces a certain volume of air and so experiences an upthrust equal to the weight of the air displaced. As long as the balloon and its contents are lower in weight than the weight of air displaced, the balloon will rise. To make up for the weight of the balloon fabric, ropes and basket, the balloon has to be filled with a gas lighter than the surrounding air. Hot air, hydrogen and helium are commonly used. Because helium gas is such an expensive and a non-renewable resource, party balloons are filled with 'balloon gas', which is mostly nitrogen but with some helium mixed in.

**Photo 7.3**
A blimp.


**Figure 7.14**




### Example 1

A large balloon is filled with hot air to a volume of 400 m$^3$. It has a total weight of 4400 N and is held to the ground by a vertical rope (Figure 7.14). Given that the density of the surrounding air is 1.2 kg/m$^3$, calculate the tension in the rope.

### Solution

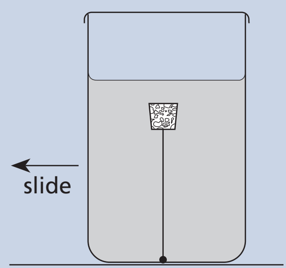
- Mass of air displaced = density of air × volume = 1.2 × 400 = 480 kg.
- Upthrust = weight of air displaced = mg = 480 × 10 = 4800 N.
- Resultant force (tension) = 4800 N (up) − 4400 N (down) = 400 N (up).

**PHYSICS FACT**

The Wright brothers published their account of the first flight in the journal *Gleaning on Bee Culture*. As manned flight didn't exist at the time there were no aviation journals — so a bee journal was the next-best thing.

### NOVEL CHALLENGE

A plastic soft-drink bottle is half-full of water. A small piece of cork is held just under the surface by a piece of string glued to the bottom. The bottle is slid to the right. *Which way does the cork move relative to the bottle — forward, backward, sideways, no movement? You'll be shocked if you try.*




### Example 2

A weather balloon has a mass when deflated (empty) of 5 kg. It is inflated to its volume of 8 $m^3$ with helium, which has a density of 0.178 kg $m^{-3}$. Find the lifting force on the balloon when the surrounding air has a density of 1.20 kg $m^{-3}$.

### Solution

- Mass of air displaced = density × volume = 1.2 × 8 = 9.6 kg.
- Upthrust = weight of air displaced = mg = 9.6 × 10 = 96 N.
- Total mass of balloon = mass of balloon + mass of helium = 5 + (8 × 0.178) = 6.4 kg.
- Weight of balloon = mg = 6.4 × 10 = 64 N.
- Lifting force = 96 N (up) − 64 N (down) = 32 N.

## Questions

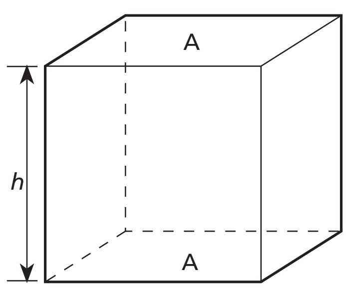
**9** A balloon is filled with hot air to a volume of 650 $m^3$. It has a total weight of 6000 N and is held to the ground by a vertical rope. Given that the density of the surrounding air is 1.18 kg $m^{-3}$, calculate the tension in the rope.

**10** Moving natural gas from the North Sea gas fields in huge dirigibles (blimps) has been proposed, using the gas itself to provide lift. Calculate the force required to tether such an airship to the ground for off-loading when it is fully loaded with $1 \times 10^6$ $m^3$ of natural gas at a density of 0.80 kg $m^{-3}$. The density of air is 1.18 kg $m^{-3}$. Neglect the weight of the airship.

**11** The Goodyear blimp *Columbia* is cruising slowly at low altitude, filled as usual with helium. Its maximum payload including crew and cargo is 1280 kg. How much more could it carry if the helium was replaced with hydrogen? The volume of the interior space is 5000 $m^3$; the density of helium is 0.16 kg $m^{-3}$ and the density of hydrogen is 0.08 kg $m^{-3}$.

## PRESSURE AND DEPTH 7.7

Figure 7.15




When you dive to the bottom of a swimming pool you can feel the increased pressure on your eardrums and lungs. When you go up a tall mountain you can feel your ears 'pop' because of the decreased air pressure. **Pressure increases with depth** because there is a greater weight of fluid on top of you.

The pressure exerted by a column of fluid on its base can be calculated by working out the weight of fluid on a given area (Figure 7.15). The base of the column in Figure 7.15 has an area $A$ and a height $h$. The density of the fluid is given the symbol $\rho$.

- Volume of fluid in column = $Ah$
- mass of fluid = $Ah\rho$
- weight of fluid = $Ah\rho\boldsymbol{g}$
- pressure = $\dfrac{\text{weight}}{\text{area}} = \dfrac{Ah\rho\boldsymbol{g}}{A} = \rho\boldsymbol{g}h \quad P = \rho\boldsymbol{g}h$

where $P$ = pressure in Pa, $\rho$ = density in kg $m^{-3}$, $A$ = area in $m^2$, $h$ = height in m, $\boldsymbol{g}$ = 10 m $s^{-2}$.

Note that pressure is independent of the area of the base. The pressure at the bottom of a large dam is no different from that at the bottom of a swimming pool if they are both the same depth.

### PHYSICS FACT

Could you have an object with a vacuum inside that would float in air? Answer: yes! You could use a titanium sphere 44 m in diameter with a wall thickness of 2 mm. It would have a 29 N upthrust. If it was 310 m in diameter and a wall thickness of 13.9 mm it could lift 1000 kg.

### Example

Determine the pressure due to the water at the bottom of a 12 m deep dam. Fresh water has a density of 1000 kg $m^{-3}$.

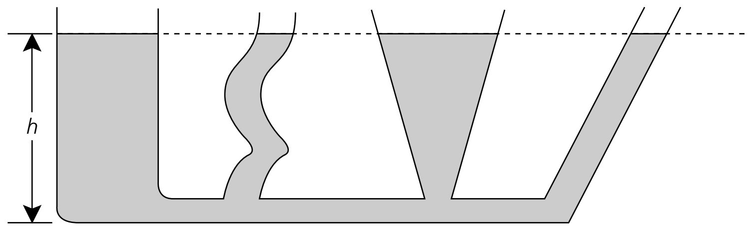



**Figure 7.16**
Pressure at a point in a fluid at rest is independent of the size or shape of the containing vessel.

### Solution

$$P = \rho g h = 1000 \times 10 \times 12 = 120\ 000 \text{ Pa } (120 \text{ kPa})$$

*Note:* this is only the pressure due to the water. The total pressure includes that of the atmosphere on top of the water (+101.3 kPa).

**INVESTIGATING**

*Did people make paper planes before the Wright brothers flew their aeroplane, Kitty Hawk, in 1903?*

**NOVEL CHALLENGE**

Definitely a tough one! A hollow steel ball with a wall thickness of 2 cm and outside diameter of 12 cm is placed in acid and it sinks. As the steel dissolves evenly from the sphere, suddenly it floats. Prove that this happens when the wall is 0.25 cm thick. The steel has a density of 7.8 $g/cm^3$ and acid has the same density as water. *Note:* $V$ (sphere) = $\frac{4}{3}\pi r^3$.

## The 'bends'

Scuba divers breathe a mixture of oxygen and the inert gases nitrogen and helium. Under pressure, the inert gases diffuse into the blood and other tissues. If the pressure is relieved too quickly by rising to the surface too fast, bubbles form in the tissues much as they do when a bottle of soft drink is opened. Sudden decompression from a long, deep dive can be fatal; even a slight miscalculation can cause serious injury to the joints or the central nervous system.

This problem is called **decompression sickness** (DCS) or 'the bends'. The most effective treatment for DCS is recompression. The diver is placed into a recompression chamber (RCC) and the pressure is increased according to a specified treatment table. The increased pressure reduces the bubble size, which helps them to diffuse back into the blood. The diver is compressed to an equivalent depth of 18 m of water and then decompressed over a period of 2–5 hours. The diver breathes oxygen from a mask while the rest of the chamber is filled with air, not oxygen, because of the fire risk. Because the attendant sits inside the chamber and breathes chamber air, great care must be taken to monitor his time and pressure profile (dive profile) to avoid the embarrassment of having an attendant emerging from the RCC with DCS.

## Diving barotraumas

As well as the 'bends', divers can suffer other problems when rising to the surface. The lungs of a diver normally contain about 6 L of air. If the diver takes a full breath of air at 20 m depth and rises to the surface, that 6 L volume expands to 18 L; in order to avoid bursting his lungs, the diver must exhale 12 L of air on the way up. Gas must be exhaled about every metre otherwise the pressure in the lungs will be sufficient to rupture them. This is called **lung barotrauma**. It is second only to drowning as a cause of death in recreational scuba divers. As swimming pools are more than 1 m deep, lung barotrauma has occurred in backyard pools.

Other types of barotraumas caused by gas expansion in the body while diving at depth are:

- mask squeeze (gas in the mask is compressed and can cause bleeding of eye tissues)
- gastrointestional barotrauma (gas in the gut expands and can cause cramps, belching and vomiting)
- dental barotrauma (gas pockets in decayed teeth may allow the teeth to implode on descent (going down) or to explode on ascent). It is not common. Diving sounds like fun!

**Photo 7.4**
Magdeburg Hemispheres. The original hemispheres were devised by Otto von Guericke, were about 30 cm in diameter and, in a famous demonstration in Magdeburg (Germany) in 1654, the air was removed and even two teams of horses (16 of them) couldn't pull the hemispheres apart.

## Pressure in the atmosphere

The relationship between pressure and altitude for a gas such as air is more complicated than the relationship between pressure and depth for a liquid because the density of a gas is not constant. It depends on the pressure. The pressure in a column of air decreases as you go up from ground level, but unlike the pressure in a water column, the decrease in air pressure with distance is not linear.

### Activity 7.9 ATMOSPHERIC PRESSURE CHANGES

**Part A**

Plot the following data (Table 7.3), which show the variation in pressure with height above Earth's surface. The pressure halves for each 5.5 km rise in altitude.

**Table 7.3**

| ALTITUDE (m) | PRESSURE (kPa) |
|---|---|
| 16 500 | 9.1 |
| 15 000 | 12.0 |
| 12 000 | 19.5 |
| 11 000 | 22.5 |
| 9 000 | 31.0 |
| 6 000 | 47.1 |
| 5 500 | 50.6 |
| 3 000 | 70.0 |
| 0 (sea level) | 101.3 |

**(a)** Estimate the pressure at 10 km and at 18 km.
**(b)** Where would pressure be zero?
**(c)** What type of relationship is this: inverse, inverse square, exponential or what?
**(d)** In 1692 Newton said that pressure and density decreased exponentially with altitude. Was he right?

**Part B**

The pressure in an aeroplane tyre is taken at ground level with a tyre pressure gauge. The plane flies to the top of a high mountain and the tyre pressure is taken again. Assume the air temperature and the mass of the plane are constant. How do the pressures compare? Even engineers argue about this one. Good luck!

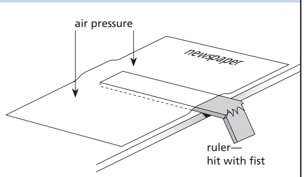
As you may gather from your graph from the above activity, in space the pressure is just about zero for there is approximately only one particle per cubic metre. Without a pressurised space capsule or space suit, animals, including humans, couldn't survive. Not only would their ears pop as the internal body pressure exploded outwards, but eyes and blood vessels would also pop. A cruel death would intervene. Unwanted pets were once put to 'sleep' by decompression at animal pounds but as the process was too distressing for both the animals and the operators the method has generally been discarded.

## Examples of decompression

- The *Los Angeles Times* reported that a flight attendant was wearing an inflatable bra when the cabin depressurised during flight. The air expanded according to Boyle's law (Chapter 11) and inflated the bra to size 46, until a woman passenger stabbed her strategically with a hat pin. This sounds like an urban myth to us!
- When a tunnel under London's Thames River had been completed and the two shafts joined, the local politicians celebrated the event at the tunnel's bottom. In the tunnel they found the champagne flat and lifeless. When they returned to the surface, however, 'the wine popped in their stomachs, distended their vests, and all but frothed from their ears'. One dignitary had to be rushed back to the depths to undergo recompression.

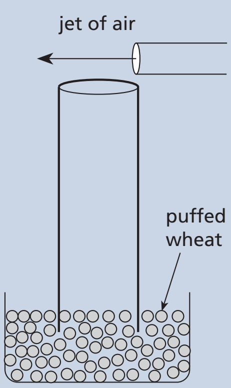
**NOVEL CHALLENGE**

A 30 cm wooden ruler was placed on a bench with 10 cm overhanging. A page of the *Courier Mail* (58 cm × 40 cm) was placed on top of the ruler on the bench. *Calculate the weight of air on the paper and predict what will happen if the overhang is given a sharp blow with your fist. You won't believe the weight. Quick now — is it more than the weight of three Corollas?*




**NOVEL CHALLENGE**

A cardboard tube is placed halfway into a container of puffed wheat. *What do you think will happen when you blow air across the top of the tube? But why, and what does Bernoulli have to do with it?*



## Questions

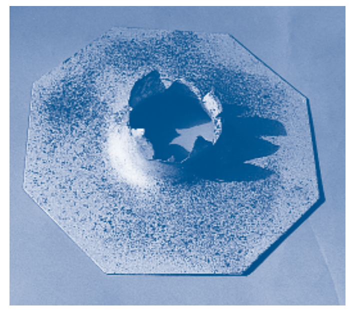
**12** Calculate the pressure in kPa at the bottom of a column of mercury 76 cm high. The density of mercury is 13 600 kg $m^{-3}$.

**13** What is the total pressure (water + atmosphere) on a diver 20 m under sea water that has a SG of 1.03? Assume atmospheric pressure is 101.3 kPa.

# 7.8 IN CLOSING

As humans explore new frontiers, research into extremes of pressure assumes great importance. At the University of Queensland, their 'hypervelocity shock tunnel' is being used in the mechanical engineering department to study the effect of shock waves on various objects such as spacecraft. An enormous piston compresses hydrogen gas to extreme pressures, which then blasts its way through a steel plate (Photo 7.5) to provide the high velocities needed for experiments. But just as important for us is the knowledge that stale eggs float, air in your brakes is bad and high blood pressure is a worry.

**Photo 7.5**
The blast-hole in the steel plate used in the shock tunnel.



## Practice questions

The relative difficulty of these questions is indicated by the number of stars beside each question number: * = low; ** = medium; *** = high.

### Review — applying principles and problem solving

***14** A person has a mass of 65 kg. The contact area between his shoes and the floor is 315 $cm^2$. Calculate the pressure he exerts on the floor.

***15** Calculate the pressure on the ground due to a Ford Falcon, mass 2240 kg, on four tyres, each with a contact area of 15 cm $\times$ 17 cm.

***16** A round swimming pool of diameter 4.5 m was filled to a depth of 1.1 m. Calculate the pressure at the bottom if you **(a)** neglect atmospheric pressure; **(b)** include atmospheric pressure (101.3 kPa).

***17** The input piston in a hydraulic hoist has a diameter of 2.50 cm, whereas the output piston is much larger at 29.0 cm. The output piston has to lift a total weight of 26 500 N. Calculate **(a)** the pressure that has to be applied; **(b)** the force needed on the small piston; **(c)** the distance the input piston will move if the output piston moves 2.0 m.

***18** A rock has a volume of 800 $cm^3$ and a weight in air of 33 N.
**(a)** What is its weight (scale reading) in water?
**(b)** Calculate the density of the rock. The density of water is 1.00 g $cm^{-3}$.

***19** Petrol has a density of 0.8 g $cm^{-3}$.
**(a)** What is its specific gravity?
**(b)** What is its density in kg $m^{-3}$?

***20** The most dense gas known is radon (Rn) with a density of 0.010 05 g $cm^{-3}$ at room temperature and pressure.
**(a)** What is the mass of a 15 L balloon full of it under these conditions?
**(b)** Convert the density to kg $m^{-3}$.

***21** A mass of small colourless mineral was measured in air using a spring balance and then its apparent mass was measured in water. The spring balance read 16.5 g in air and 10.6 g when the specimen was in water. Calculate the SG.

***22** A pair of Scuba tanks has a volume of 22.4 L and a mass of 24 kg when full. What is their weight (scale reading) in **(a)** air; **(b)** salt water?
**(c)** What mass would they have to be to have neutral buoyancy in this water? The SG of salt water is 1.02.

**NOVEL CHALLENGE**

A square pond measures 100 m by 100 m. A block of ice with a mass of 1000 kg is floating freely in the pond. How far will the water level rise when the ice melts? You won't like the answer. (The density of water is 1000 kg $m^{-3}$; that of ice is 917 kg $m^{-3}$.)

**Figure 7.17**
For question 33.

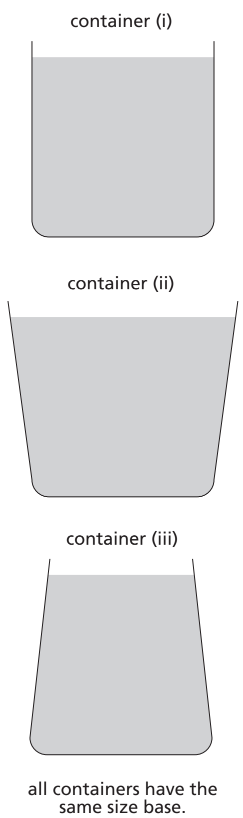
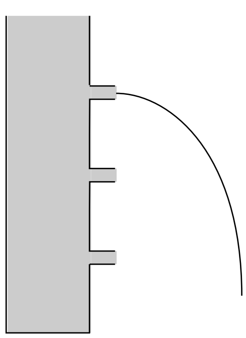



**Figure 7.18**
For question 34.



***23** A float made of polystyrene foam floats with one-fiftieth of its volume below the water level. Calculate the density of the polystyrene.

****24** A 50 cm piece of high density polythene water pipe is made to float upright in a container of water. If the pipe has a density of 0.89 g cm$^{-3}$, how much of the pipe will be above the surface?

***25** When a cube of ice is placed in tap water, 94% of its volume is submerged.
**(a)** What is the density of the ice cube?
**(b)** How much would be submerged if it was floated in salt water of density 1.02 g cm$^{-3}$?

****26** During the Second World War, a damaged freighter that was just able to float in the salty water of the North Sea sank as it came up the Thames estuary toward the London docks. Why?

****27** Beer hydrometers are calibrated at 15°C and if the temperature is different, a correction has to be applied. If a hydrometer placed in a beer 'wort' at 25°C gave a reading of 1042 (1.042 g cm$^{-3}$) would you expect the real density to be higher or lower than this value? Explain your answer.

****28** A girl has several large rocks in a row boat and she rows out into the middle of a pond. To make some room she throws the rocks overboard.
**(a)** What happens to the water level on the side of her boat?
**(b)** What happens to the water level in the pond?
**(c)** Design your own experiment to test your answer in the classroom. Write down your results. They may surprise you.

***29** Why do you sometimes need to punch two holes in a can of pineapple juice to make it come out evenly?

****30** Hydrogen appears to have negative weight as you can't weigh a balloon full of it on a balance. Design an experiment to weigh a litre of hydrogen gas.

## Extension — complex, challenging and novel

*****31** A steel ball bearing is placed in a bowl of mercury.
**(a)** Given that the density of steel is 8.0 g/cm$^3$ and that of mercury 13.6 g cm$^{-3}$, calculate what fraction of the volume of the sphere is submerged.
**(b)** Suppose we pour some water on top of the mercury. Does the steel ball sink more deeply or less deeply in the mercury?

*****32** Crew members attempt to escape from a damaged submarine 100 m below the surface.
**(a)** What force must they apply to a pop-out hatch, which is 1.2 m by 0.60 m, to push it out?
**(b)** What mass is this equivalent to lifting? Could a lone sailor manage? Assume the density of sea water is 1025 kg m$^{-3}$.

*****33** Three containers are set up and filled to the same height with water (Figure 7.17).
**(a)** Which has the greatest volume of water in it?
**(b)** Which has the greatest weight of water in it?
**(c)** Which has the greatest mass of water in it?
**(d)** Which has the greatest pressure at the bottom?

*****34** A can 40 cm tall has small holes in it at 10 cm, 20 cm and 30 cm from the base (see Figure 7.18). It is filled with water. Where do the streams of water strike the ground? To make this calculation you need to use Bernouli's equation, which can be reduced to: pressure = $\rho \boldsymbol{g}h = \frac{1}{2}\rho \boldsymbol{v}^2$. This reduces further to $\boldsymbol{v} = \sqrt{2\boldsymbol{g}h}$, where $h$ equals the height of water above the hole, and $\boldsymbol{v}$, the velocity of the water out of the hole.

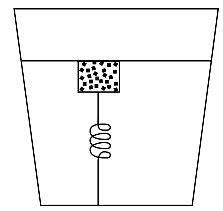
****35** Imagine a glass of water sitting on a table with a few cubes of ice floating in it. The water is level with the top of the glass and the ice projects above the top. As time goes by the ice melts. Will the water overflow the glass?

*****36** Consider two balloons of equal volume (400 000 L) and mass (200 kg), one filled with hydrogen, the other with helium. Helium is twice as dense as hydrogen (hydrogen — 0.09 g/L; helium — 0.18 g/L). The density of air is 1.3 g/L.
 **(a)** How do their lifting abilities compare?
 **(b)** Will the hydrogen balloon be able to lift twice weight as the helium balloon? Explain.

*****37** Two identical buckets are filled to the brim with water but one has a block of wood floating in it. Which bucket is the heavier?

*****38** When a cork is placed in a bucket of water it floats with one-quarter of its volume submerged. Imagine we attach a small spring to the cork and attach it to the inside bottom of the bucket and adjust it so that it is just submerged (the top of the cork is now level with the surface of the water) as in Figure 7.19. The weight of the cork and tension in the spring now equal the upthrust. The bucket is dropped off a tall building. What would happen to the cork during the fall?

**Figure 7.19**
For question 38.



*****39** The *Guinness Book of Records* lists the greatest ocean descent as that of the US Navy underwater research vessel (a bathyscaphe) the *Trieste*, which reached a depth of 10 916 m on January 23 1960. It says that the pressure at this depth was 1187 kgf/cm$^2$ and the temperature 3°C. A *kgf* is a non-SI unit known as a *kilogram force*. This is the force of gravity acting on 1 kg. Convert the pressure to pascals and calculate the average density of seawater above the bathyscaphe. Neglect atmospheric pressure.

*****40** Calculate the difference in blood pressure between the brain and the foot of a person of height 1.83 m. The density of blood is $1.06 \times 103$ kg m$^{-3}$.

*****41** The human lungs can operate against a pressure difference of about one-twentieth of an atmosphere. If a diver uses a snorkel for breathing, how far below the surface can he or she swim?

*****42** About one-third of the body of a person swimming in the Dead Sea will be above the water line. Assuming that the density of a human is 0.98 g cm$^{-3}$, find the density of the water in the Dead Sea.

*****43** Imagine a U-tube containing some mercury. The mercury level is equal on both sides of the tube. An equal volume of water is added to one side. How will their levels now compare? Make a statement about the relative heights of the two columns.

*****44** Prove that hydrogen provides only an extra 8% lift compared to helium for a balloon of mass 2.13 kg, even though helium is twice as dense as hydrogen. See Example 2 on page 177 for density data.

*****45** A 20 cm diameter spherical beach-ball floats with 1 cm submerged. Calculate the mass of the ball. You'll need extra maths formulas.

*****46** A cylindrical log 1 m long and 20 cm diameter floats with 8 cm submerged. Calculate its mass and density. Extra maths formulas required.