Chapter 7 – Pressure

Subject content

Content
- Pressure
- Pressure differences
- Pressure measurement

Learning outcomes
(a) define the term pressure in terms of force and area
(b) recall and apply the relationship pressure = force / area to new situations or to solve related problems
(c) describe and explain the transmission of pressure in hydraulic systems with particular reference to the hydraulic press
(d) recall and apply the relationship pressure due to a liquid column = height of column × density of the liquid × gravitational field strength to new situations or to solve related problems
(e) describe how the height of a liquid column may be used to measure the atmospheric pressure
(f) describe the use of a manometer in the measurement of pressure difference

Definitions

Term	Definition	SI unit
Pressure	Force acting per unit area	pascal (Pa)
Pascal's Principle	When pressure is applied to enclosed liquid, pressure is transmitted equally to all other parts of liquid	
Atmospheric pressure	Pressure exerted by atmosphere on Earth's surface	pascal (Pa)

Formulae

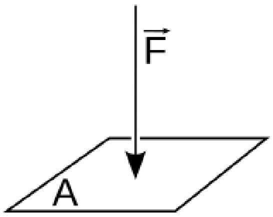
Pressure	Pressure in liquid
$P = \frac{F}{A}$	$P = \rho g h$
Hydraulic machine	
$\frac{F_X}{A_X} = \frac{F_Y}{A_Y}$	$F_X \times d_X = F_Y \times d_Y$

7.1 Pressure

Pressure

Pressure

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



where P = pressure (in Pa)
F = force (in N)
A = area of contact (in m^2)

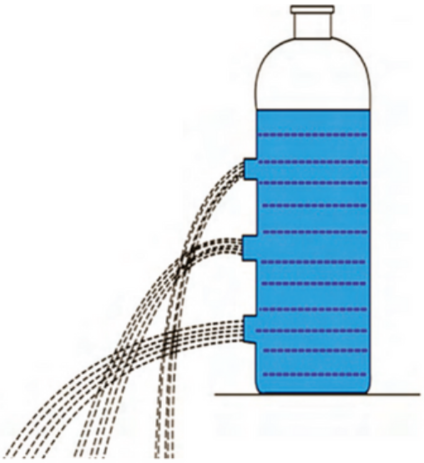
1 Pa = 1 newton per square metre (Nm^{-2})

7.2 Pressure in Liquids

Pressure at certain depth of liquid

Liquid pressure

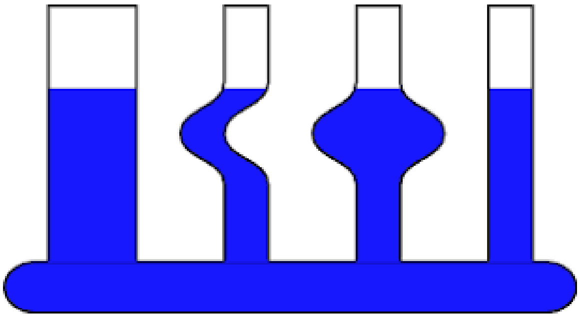
$$\boldsymbol{P = \rho g h}$$



where ρ = density (in kg/m^3)
g = gravitational field strength (in N/kg)
h = height (in m)

Liquid pressure
- does not depend on volume
- does not depend on cross-sectional area
- depends on **vertical height** of liquid column

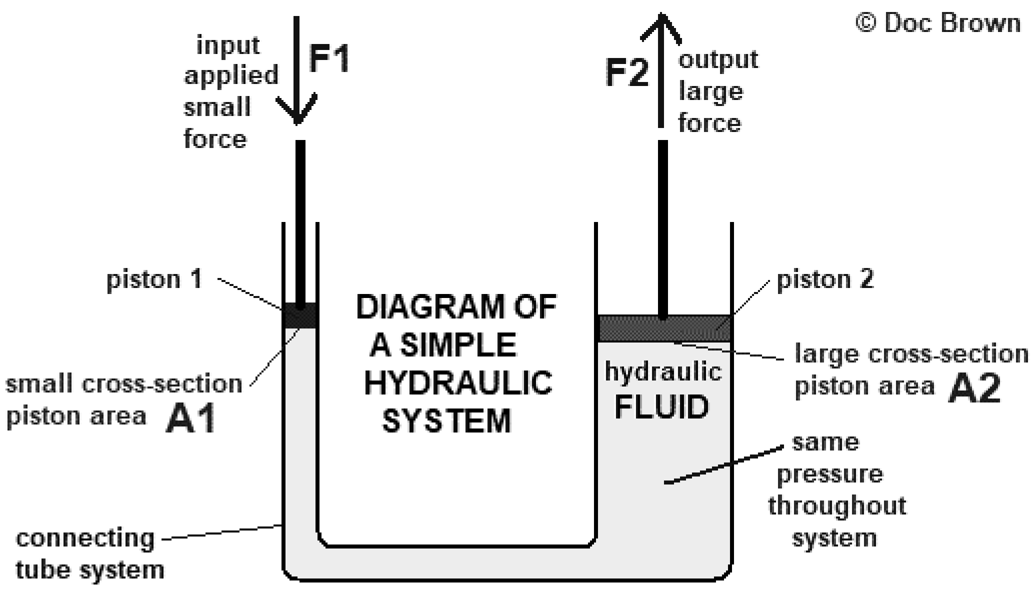
Pascal's vase



Pascal’s Principle

Pascal’s Principle

When pressure is applied to enclosed liquid, pressure is transmitted equally to all other parts of liquid



Hydraulic machine → use liquid to transmit pressure

- Application
  - Hydraulic press - lift up cars / heavy objects
  - Car hydraulic disc brake system
- Functioning
  - Small force F_X applied on small piston with area A_X
  - Pressure P_X is transmitted equally to every part of liquid
  - Larger force acts on bottom of large piston → lift large load with relatively small force

$$P_Y = P_X$$
$$F_Y / A_Y = F_X / A_X$$
$$A_Y > A_X \Rightarrow F_Y > F_X$$

- Principle of Conservation of Energy:

$$F_X \times d_X = F_Y \times d_Y$$

7.3 Gas Pressure

<u>Atmospheric pressure</u>

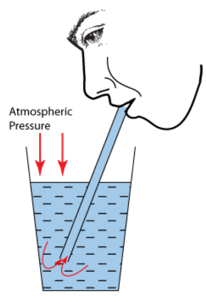
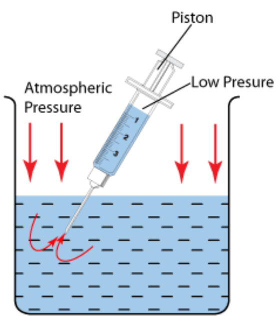
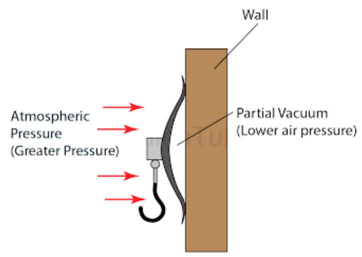
Atmospheric pressure

- air molecules move in continuous, random, high speed manner
  - collide with surfaces and exert a force
  - pressure exerted on surface = average force per unit area
- difference in pressure → resultant force (direction: high → low pressure area)
- decreases with increasing altitude

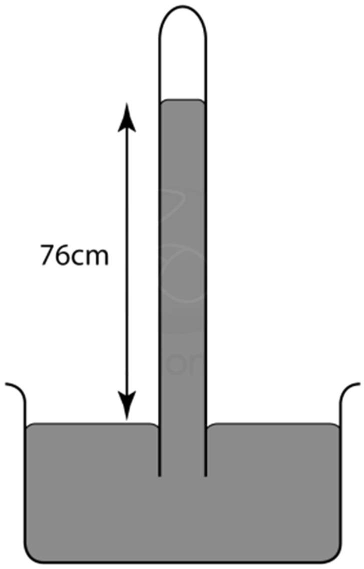
Atmospheric pressure at sea level:

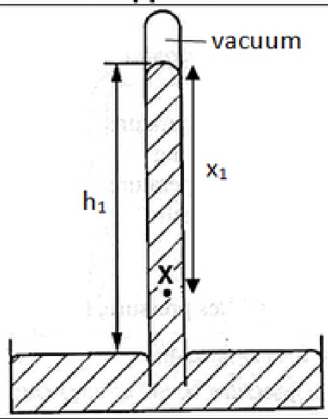
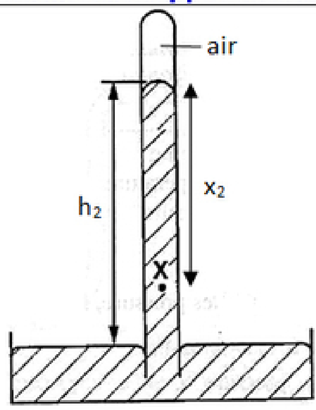
- **1.013 × 105 Pa**
- **760 mmHg**
- **1 atmosphere**

Applications:

Scenario			
Removal of air	Air is removed from inside of mouth	Plunger moves up and air pressure inside barrel is reduced	As suction pad is pressed, air is removed between pad and wall
Comparison of pressure inside and outside	$P_{atm} > P_{mouth}$	$P_{atm} > P_{plunger}$	$P_{atm} > P_{pad}$
Pressure difference	✓	✓	✓
Net force applied	push water into mouth	push water up into nozzle	push pad against wall, hold it firmly against wall

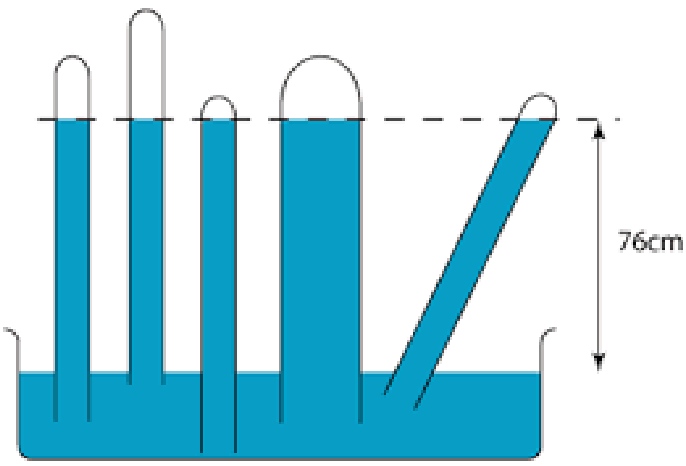
<u>Barometer</u>



<table>
<tr><th>No air trapped in the tube</th><th>Some air trapped in the tube</th></tr>
<tr><td></td><td></td></tr>
<tr><td>$p_{atm} = h_1 \rho g$
$p_x = x_1 \rho g$</td><td>$p_{atm} = h_2 \rho g + p_{air}$
$p_x = x_2 \rho g + p_{air}$</td></tr>
<tr><td colspan="2">$x_1 > x_2$
$h_1 > h_2$</td></tr>
</table>

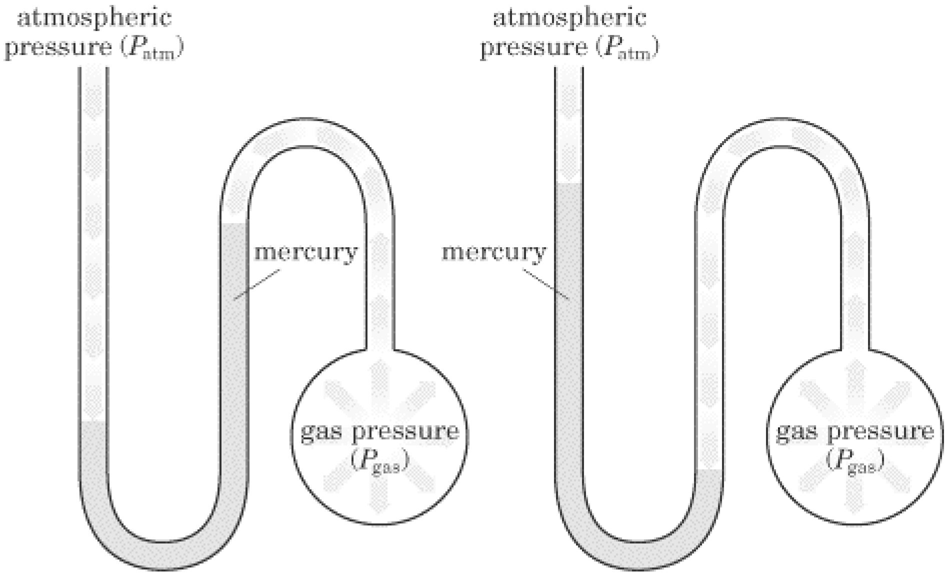
Vertical height of mercury column

- measured from top of column → exposed level
- dependent only on **<u>atmospheric pressure outside tube</u>**
- remains <u>same</u> even if column is tilted / cross-sectional area varies



Manometer

Measure difference in pressure

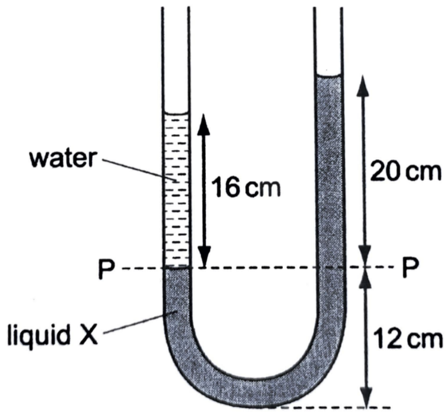


Gas pressure higher than P_0	Gas pressure lower than P_0
Gas pressure push liquid level downwards to equalise pressure difference	Atmospheric pressure push liquid level downwards to equalise pressure difference
$P_A = P_0 + \rho gh$	$P_A = P_0 - \rho gh$

Typical questions

Multiple choice questions

1 A manometer contains water and a liquid X. The two liquids do not mix.



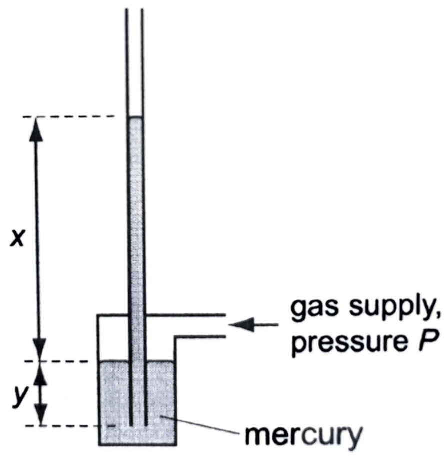
The pressure at level P in the water is equal to the pressure at level P in liquid X.
The density of water is 1000 kg/m^3.
What is the density of liquid X? (2011 P1 Q10)

A 500 kg/m^3
B 800 kg/m^3
C 1250 kg/m^3
D 2000 kg/m^3

2 One side of a vertical garden fence has an area of 4.0 m^2. A strong wind blows on one side of the fence and increases the pressure to 105 kPa. The pressure on the other side of the fence is 103 kPa.
What is the resultant force on the fence? (2013 P1 Q13)

A 500 N
B 8000 N
C 16000 N
D 420000 N

3 An open tube stands, with one end in mercury, in a chamber that is connected to a gas supply. The pressure of the gas is *P* metres of mercury. The atmospheric pressure is h metres of mercury.

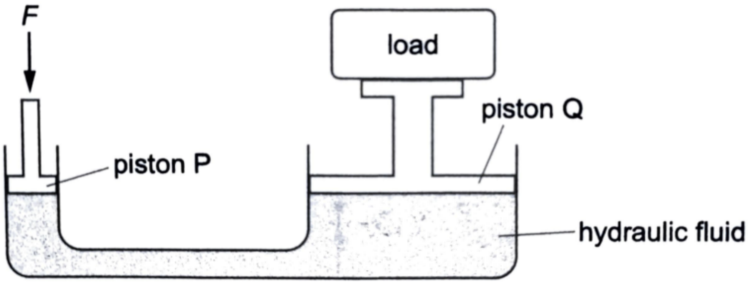


If x and y are measured in metres, the pressure P in metres of mercury is equal to:

(2013 P1 Q14)

A $x + h$
B $x - h$
C x
D $x + y$

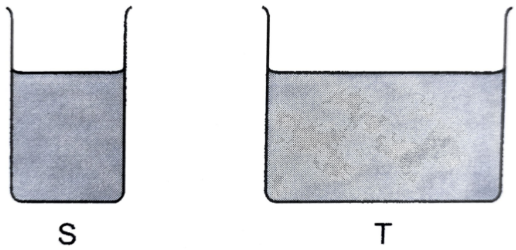
4 A hydraulic jack is used to lift a load of mass 1000 kg by applying a force F to piston P.



The cross-sectional area of piston P is 100 cm^2 and the cross-sectional area of piston Q is 500 cm^2. The gravitational field strength g is 10 N/kg.
What is the value of the force F? (2016 P1 Q11)

A 200 N
B 2000 N
C 5000 N
D 50000 N

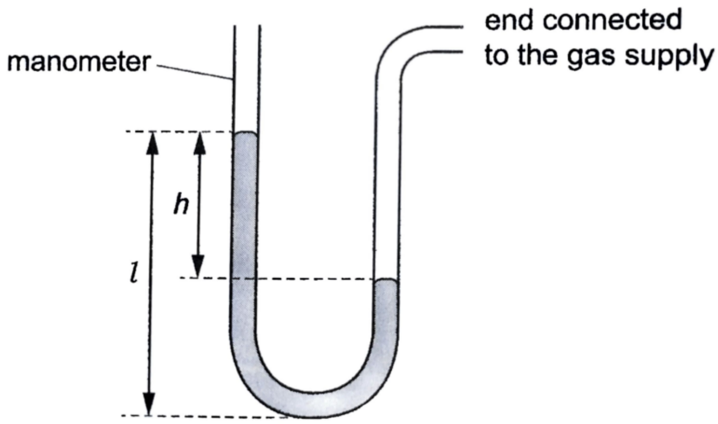
5 Two beakers S and T are filled to the same level with water. The area of the base of S is less than that of T.



Which statement is correct? (2018 P1 Q13)

A The force due to the liquid on the base of S is greater than the force on the base of T.
B The force due to the liquid on the base of S is the same as the force on the base of T.
C The pressure on the base of S is less than the pressure on the base of T.
D The pressure on the base of S is the same as the pressure on the base of T.

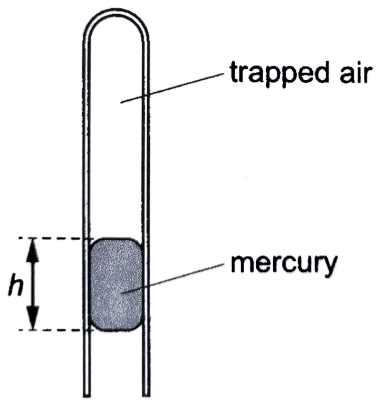
6 The diagram shows the difference in liquid levels in a manometer that is connected to a gas supply.



Height h is measured.
Which quantity also needs to be known in order to calculate the excess pressure of the gas supply compared to atmospheric pressure? (2018 P1 Q14)

A the cross-sectional area of the tube
B the density of the gas
C the density of the liquid
D the length l

7 A uniform tube, sealed at one end, is held vertically with the closed end at the top. It contains a thread of mercury that traps a column of air. The other end of the tube is open to the atmosphere.



The pressure due to a thread of mercury of height h is 0.18×10^5 Pa and the atmospheric pressure is 1.0×10^5 Pa.
What is the pressure of the trapped air? (2019 P1 Q12)

A 0.18×10^5 Pa
B 0.82×10^5 Pa
C 1.0×10^5 Pa
D 1.18×10^5 Pa

Structured questions

1 A suction cup is used as a support from which an ornament hangs. The area of the flat surface covered by the cup is 5.0 cm^2.

(a) Explain how the suction cup can be used to support the ornament. [3]

- As the suction pad is pressed, some air is removed between the pad and wall.
- Atmospheric pressure outside the pad is larger than the pressure inside it.
- The pressure difference results in an upward net force that can support the weight of the ornament.

(b) Can an ornament with a mass of 8.0 kg be hung on this suction cup without dropping? Justify your answer. (Atmospheric pressure is 1.0×10^5 Pa) [2]

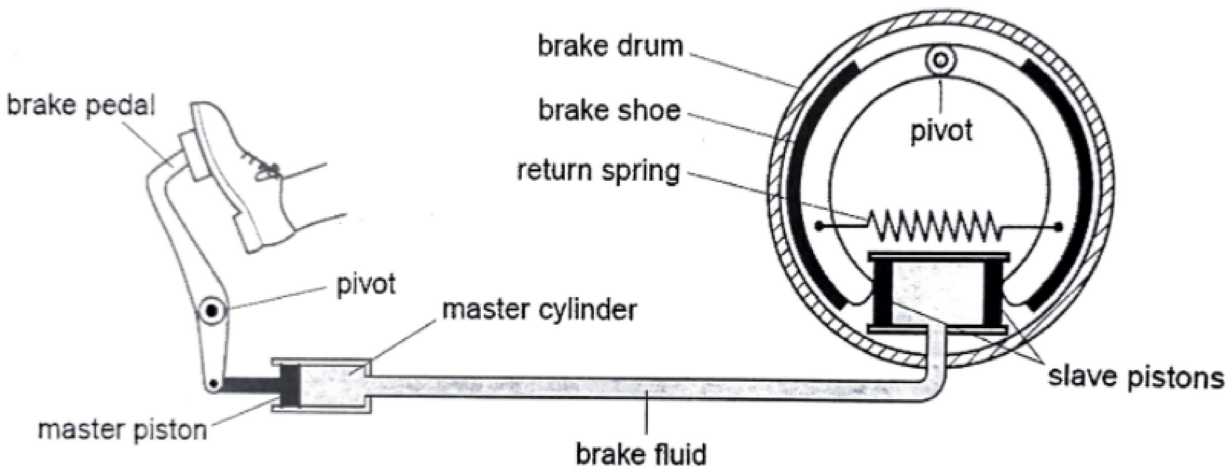
Greatest weight
= pressure difference × area
= $(1.0 \times 10^5) \times (5.0 \times 10^{-4})$
= 50 N
= 5.0 kg

∴ Since the maximum mass that the suction cup can hold is 5.0 kg,
the ornament of mass 8.0 kg cannot be hung without dropping.

2 Why is mercury used in the barometer instead of water? [1]

The density of water is much lower than mercury (1000 kg/m^3 compared to 13600 kg/m^3). The barometric height using water would have been 13.6 times greater than 760 mm at 10.3 m high, which would make it impractical.

3 The figure below shows a car braking system. The brake fluid is oil.



The brake drum rotates with the wheel of the car.

(a) Explain how pushing the brake pedal makes the brake shoes rub against the drum. [2]

Force exerted by the master piston on the brake fluid creates a pressure that is transmitted undiminished to the slave pistons as liquids are incompressible.
The pressure transmitted provides a force on each slave piston which pushes the brake shoe outwards against brake drums, thus rubbing against the drum.

(b) The cross-sectional area of the master piston is 2.0 cm^2. A force of 140 N is applied to the master piston.

(i) Calculate the pressure created in the brake fluid by the master piston in Pa. [1]

$P = 140 / 0.0002 = 7.0 \times 10^5$ Pa

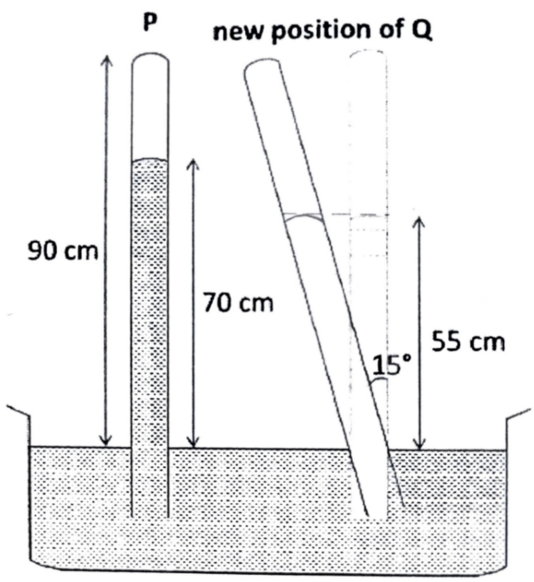
(ii) The cross-sectional area of each slave piston is 2.8 cm^2.
Calculate the force exerted on each slave piston by the brake fluid. [1]

$F = (7.0 \times 10^5) \times 0.00028 = 196$ N

(iii) Explain why the force exerted on the master piston is greater than the force applied by the foot on the brake pedal. [2]

The perpendicular distance from the piston to the pivot is smaller than the perpendicular distance from the foot to the pivot.
Since Moment = force × perpendicular distance and clockwise moment = anticlockwise moment,
thus force exerted on the master piston is greater than that on the brake pedal.

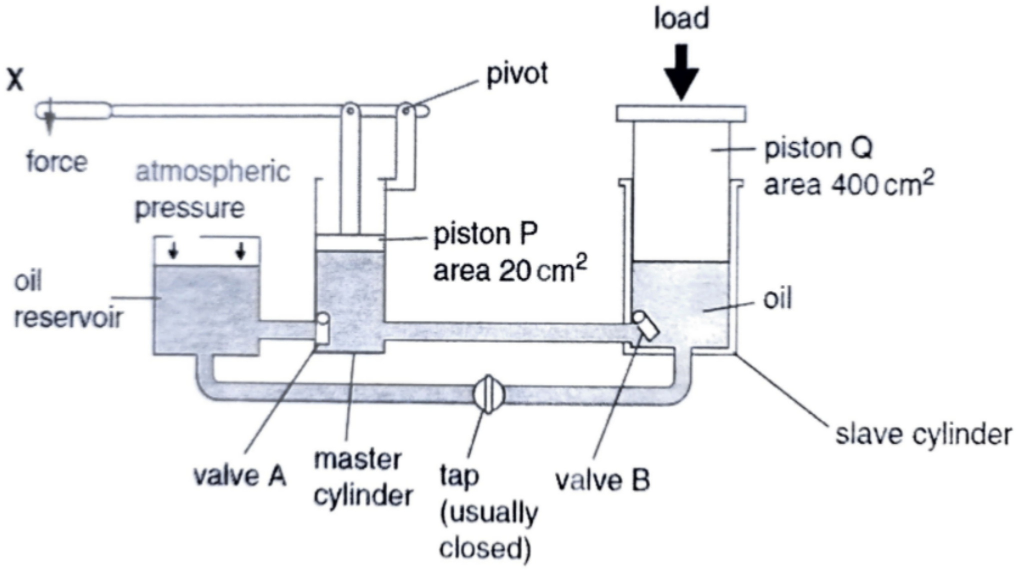
4 Due to a small knock, tube Q is slightly shifted and ends up at an angle 15° to the vertical, as shown in the figure below.



On the diagram, draw the new level of the mercury meniscus in tube Q.
Explain your answer. [1]

Liquid pressure is dependent on the vertical height of the liquid column above it and not the geometrical orientation of the column.

5 The figure below shows a hand-operated hydraulic press.



A force is applied downwards at X as shown. Piston Q rises in the slave cylinder. The area of piston P is 20 cm^2 and the area of piston Q is 400 cm^2.

(a) Explain, in detail, how pushing X downwards causes piston Q to rise. State clearly what happens to valve A and valve B. [2]

When X is pushed down, piston P exerts a pressure in the oil which is transmitted undiminished throughout oil and acts on piston Q, creating a force on piston Q.
Oil moves to the slave cylinder, keeping valve B open and valve A shut.

(b) After X in the figure above is pushed down, it is lifted up again. State what happens, as X is lifted, to valve A, valve B and piston Q. [3]

- Valve A opens.
- Valve B shuts.
- Piston Q remains unchanged.

(c) Give 2 reasons why a small force exerted at X can lift a music heavier load at Q. [2]

Moments

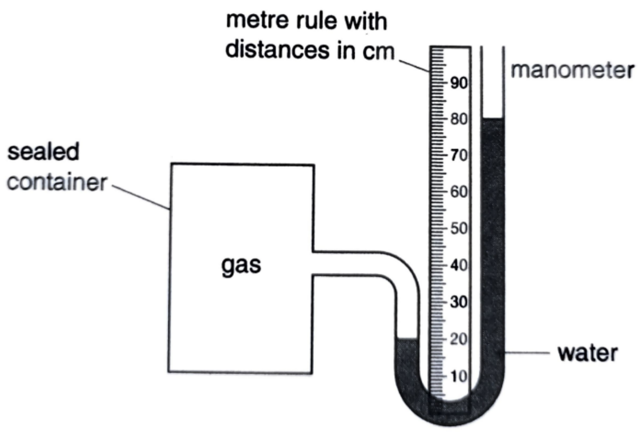
- Perpendicular distance between the pivot to the force at X is greater than the perpendicular distance between the pivot to force exerted at piston P.
- Hence, a small force at X will result in a large force at P,
- as Moment = Force × perpendicular distance, and clockwise moment = anticlockwise moment.

Pressure

- Area of piston Q is much larger than that of piston P,
- so that force at Q will be much greater than P
- because pressure is transmitted in the oil (liquid).

6 The figure below shows a manometer attached to a sealed container filled with gas.

(2011 P2A Q1)



The water in the manometer has a density of 1000 kg/m^3.
Atmospheric pressure is 1.0×10^5 Pa and the acceleration of free fall g is 10 m/s^2.

(a) Define pressure. [1]

Pressure is the force acting per unit area.

(b) Calculate the pressure of the gas inside the sealed container. [2]

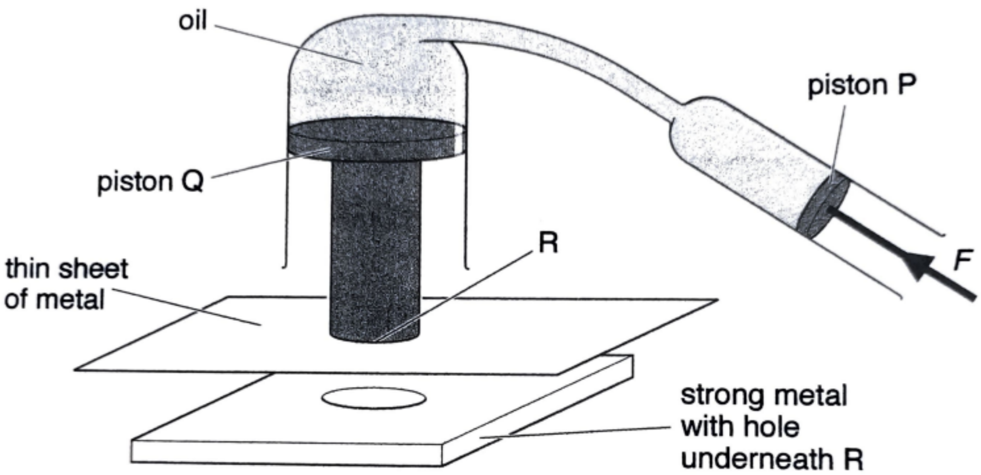
Pressure of gas
= Difference in pressure + atmospheric pressure
= $\rho gh + (1.0 \times 10^5)$
= $(0.6)(1000)(10) + (1.0 \times 10^5)$
= 1.06×10^5 Pa

(Note: A manometer measures a difference in pressure. Units of height must be converted to metre, for units of pressure to be in pascals.)

(c) Using ideas about molecules and the definition of pressure, explain why the pressure of the gas in the container rises when the temperature increases. [3]

When the temperature of the gas increases, the thermal energy supplied is converted to the kinetic energy of the molecules. The molecules are now moving faster. As such, they collide with the walls of the container more frequently, and with a greater force. Since pressure is the sum of forces acting per unit area, the pressure increases.

7 The figure below shows a hydraulic press used to punch a hole in a thin sheet of metal. (2015 P2A Q3)



(a) The operator exerts a force F on piston P. The atmosphere also exerts a force on P in the same direction as F. Piston P remains stationary.
The pressure inside the oil is 3.0×10^5 Pa and atmospheric pressure is 1.0×10^5 Pa.
The cross-sectional area of piston P is 5.0×10^{-5} m^2.
The weight of piston Q is negligible.

(i) Calculate the force that the oil exerts on piston P. [2]

$P = F / A$
$F_{oil} = P \times A = (3.0 \times 10^5)(5.0 \times 10^{-5}) = 15$ N

(ii) Calculate the force that the atmosphere exerts on piston P. [1]

$F_{atm} = (1.0 \times 10^5) \times (5.0 \times 10^{-5}) = 5$ N

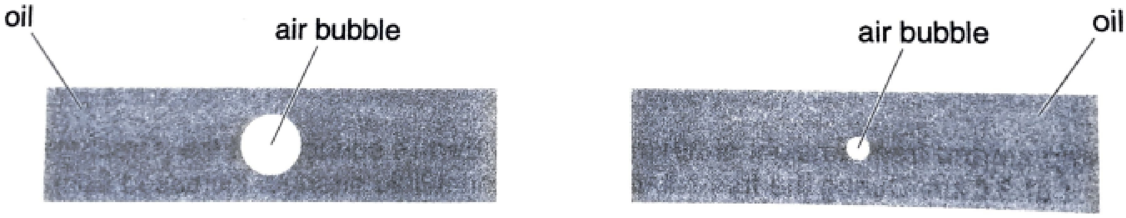
(iii) Calculate the value of *F*. [1]

Given that piston P remains stationary, the forces are balanced. This means the 15 N force from the oil must be balanced by the force exerted from the atmosphere (5 N), as well as F.
F = 15 - 5 = 10 N

(iv) Explain how this apparatus ensures that the force exerted on the metal plate at R is larger than *F*. [1]

Since the pressure in the oil is the same, and there is a greater cross-sectional area at piston Q, a larger force will be exerted on the metal plate.

(b) A small bubble of air in oil is shown in the left figure below.



When the pressure in the oil increases, the air bubble decreases in size, as shown in the right figure below. The temperature does not change.

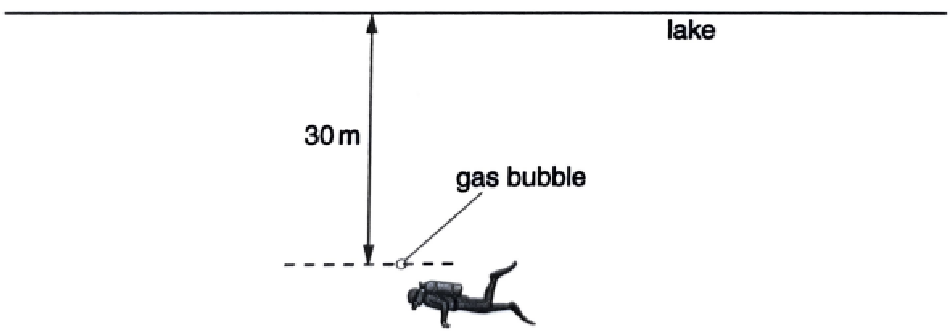
(i) Explain, using ideas about molecules, why the pressure of the air inside the bubble is larger in the left figure than in the right figure. [2]

- The number of molecules in the air bubble remains the same, but they are now squeezed into a smaller space / volume. As a result, they will hit the surface of the bubble more frequently, as they are in constant motion.
- This means that there would be a larger force exerted on the surface of the bubble, and since the surface area of the bubble is also smaller, a greater pressure is exerted.

(ii) Suggest why the hydraulic press does not work properly if the oil contains bubbles of air. [1]

Bubbles of air are highly compressible, thus if the oil contains bubbles, instead of transmitting the pressure to the other piston, the force would be first needed to compress the bubbles first.

8 A bubble of gas rises from a diver to the surface of a lake, as shown in the figure below.

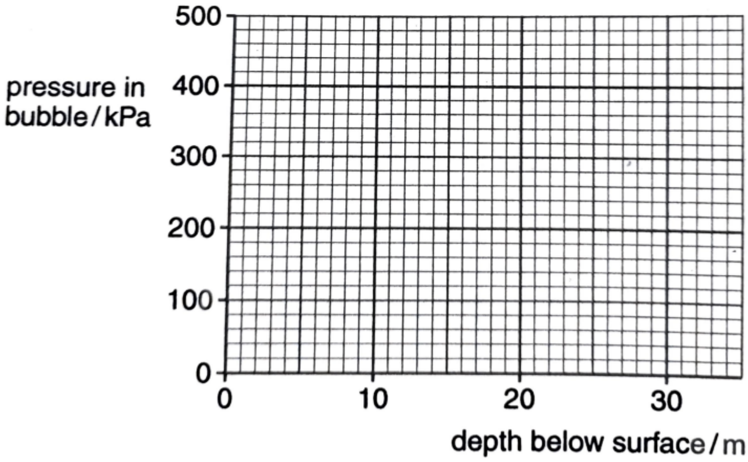


The bubble is 30 m below the surface of the lake. (2013 P2B Q12a OR)

(a) The pressure of the atmosphere is 100 kPa and the density of the water is 1000 kg/m^3. The gravitational field strength g is 10 N/kg.
Calculate the pressure in the bubble at a depth of 30 m. [3]

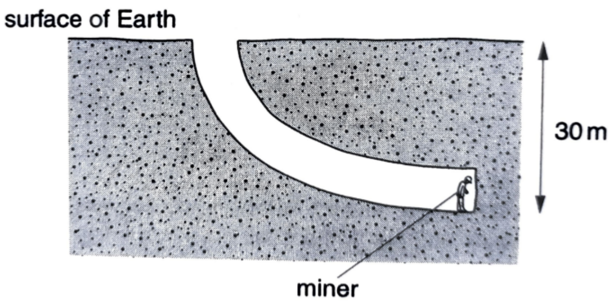
Pressure at depth of 30 m
= pressure due to atm + pressure due to water
= 100 000 Pa + (1000)(10)(30)
= 400 000 Pa
= 400 kPa

(b) In the figure below, draw a graph to show how the pressure of gas in the bubble changes with depth below the surface of the lake. [1]



(Note: At the surface (when depth = 0), the pressure is 100 kPa due to the atmosphere. We have calculated in (i) that the pressure at 30 m is 400 kPa.)

(c) The figure below shows a miner below the surface of the Earth.



The atmospheric pressure 30 m below the surface of the Earth is almost the same as at the surface. The pressure in water at a depth of 30 m is very different from that at the surface.
Explain this. [1]

<u>The pressure underground is due to the air column above the miner. However, as the density of air is much less compared to the density of water, therefore the pressure at a depth of 30 m of water is very different from that of 30 m underground.</u>