Newtonian Mechanics

Forces, Density and Pressure

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What is a Force?

- We can define a FORCE as a push or a pull due to the interaction between objects which produces or tends to produce motion; stops or tends to stop motion; changes or tends to change motion.

- There are various forces experienced in our daily life, for example, gravitational force, electrical force, magnetic force, normal reaction, tension, friction, viscous force and upthrust.

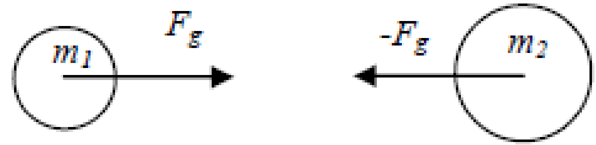
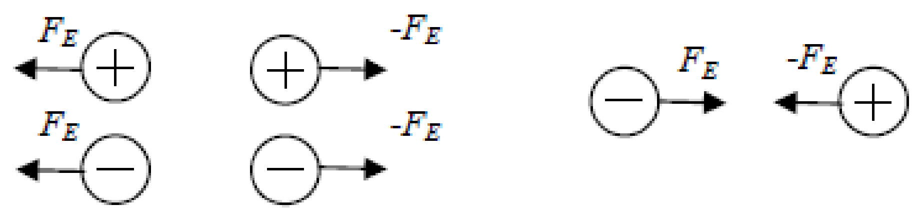
Types of Forces

- **Gravitational Force, Electric Force, Magnetic Force and Weak force.**
- Four types of fundamental forces govern the physical universe. They are gravitational force, electromagnetic force, nuclear force and weak force.

The forces on mass and charge in uniform gravitational and electric fields.

Field

- In Physics, a field refers to a region of space within which a force is experienced.
- There are several different types of forces that act on different types of "objects". For all these types of forces, Newton's laws of motion still apply.
- A gravitational field due to a mass is a region of space within which a gravitational force is experienced by another mass. An electric field due a charge is a region of space within which an electric force is experienced by another charge. A magnetic field is a region of space within which a magnetic force is experienced by a moving charge.

Type of forces	Nature of forces	Description
Gravitational Force, F_g	Acts on masses	• Attractive force that acts between any two masses. • Direction of force always in the direction of the external gravitation field strength 
Electric Force, F_E	Acts on electric charges	• Attractive or repulsive force that acts between any two electric charges. • For positive charges, direction of force is always in the direction of an external electric field • For negative charges, direction of force is always opposite to the direction of an external electric field 
Magnetic Force, F_M	Acts on current carrying conductors, moving charges or magnets	• If the conductor is placed parallel to the magnetic field, no force is experienced.  • The direction of magnetic force is perpendicular to the magnetic field and is given by **Fleming's Left Hand Rule**.

The origin of the upthrust acting on a body in a fluid

Upthrust acting on a body in a fluid

- A fluid will exert a **force upward** on a body if it is partly or wholly submerged within it. This is because the deeper into a fluid you go, the greater the weight of it and so the greater the pressure.
- This difference in pressure between the top and the bottom of the object produces an upward force on it. This is called **Upthrust.**

Using the equation p = ρgh

A fluid is a collection of molecules that are randomly arranged and held together by weak cohesive forces and by forces exerted by the walls of a container i.e. it is a substance which can flow. Both liquids and gases are fluids.

Fluid pressure increases with depth. Water pressure increases with depth. Likewise, atmospheric pressure decreases with increasing altitude (height).

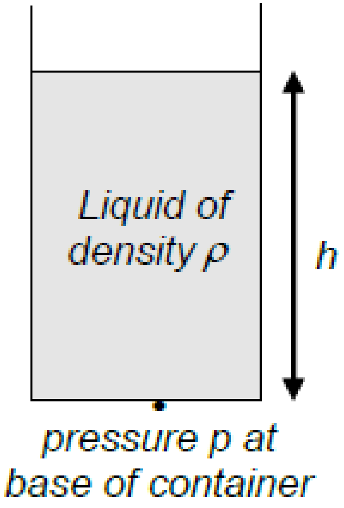
Consider a cylinder of fluid with height h as shown in Figure 4,

The fluid pressure p (at the base of container) is given by

$$\boxed{p = \rho g h}$$

where:

- p is the pressure <u>due to the fluid</u> (liquid or gas) at depth h, (unit: Pa)
- ρ is the density of the fluid, (unit: kg m^{-3})
- g is the acceleration of free fall, (unit: m s^{-2})
- h is the depth of the fluid, (unit: m)



<u>Figure 4</u>

Note:

1. Pressure is a scalar quantity.

2. The fluid density ρ is assumed to be constant (i.e. the fluid is incompressible)

3. The fluid pressure p is equal (acting in all directions) at all points having the same depth, independent of the shape of the container.

4. The equation $p = \rho g h$ allows the pressure due to the fluid to be calculated. It should be remembered that the actual pressure at depth h in a liquid would be given by

$$\text{pressure at depth } h = \underbrace{\rho g h}_{\text{(pressure due to fluid only)}} + \text{atmospheric pressure at liquid surface}$$

Sample Problem

Consider a uniform cylinder of cross-sectional area A and height h totally immersed in a liquid

The top and bottom face of the cylinder are at depth of h_1 and h_2 respectively from the surface of the liquid.

Pressure at the top face $= h_1 \rho\, g$

Force at the top face $= h_1 \rho\, gA$

Pressure at the bottom face $= h_2 \rho\, g$

Force at the bottom face $= h_2 \rho\, gA$

As different forces act on the two faces, a resultant force known as the upthrust is exerted on the cylinder.

Hence upthrust $= F_2 - F_1$

$= h_2 \rho\, gA - h_1 \rho\, gA$

$= \rho\, g\, A\, (h_2 - h_1)$

$= \rho\, g\, V$ where V is the volume of the cylinder

$= mg$ where m is the mass of liquid displaced by volume V

The upthrust on an object immersed in a liquid is equal to the weight of the liquid displaced by that object. This statement is commonly remembered as **Archimedes' Principle**.

- If the weight of an object is greater than the upthrust, it will sink (Fig 5.3a).

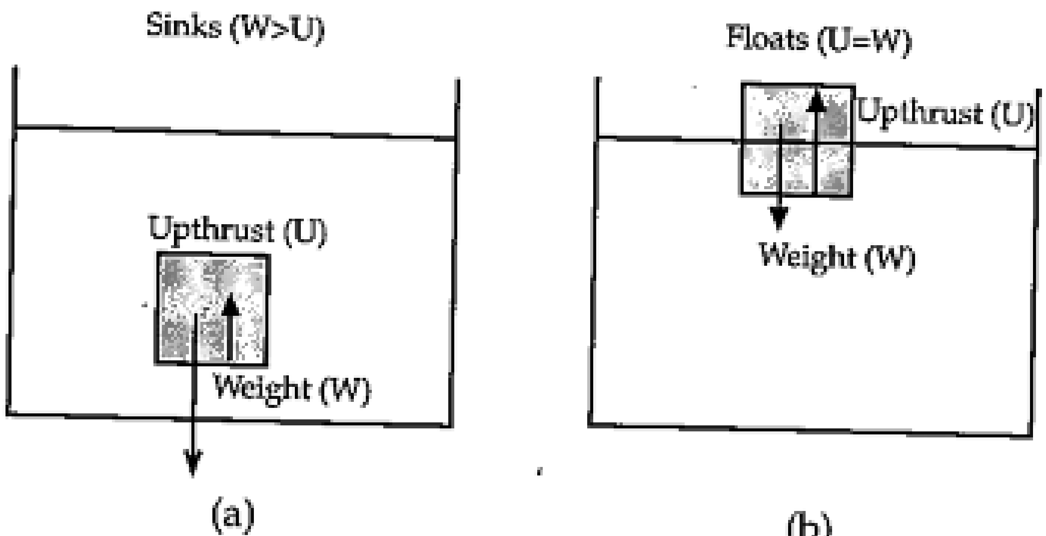


Fig 5.3 Object remains in equilibrium (floats) only when U = W

If the weight of an object is equal to the upthrust, it will float (Fig 5.3b ; This is known as the **principle of floatation.** A ship made of steel can float because its internal hollow volume displaces a large amount of water which in turn generates sufficient upthrust to keep the ship in equilibrium. A submarine can rise or sink at will because it contains ballast tanks that can expel or take in water. The variable upthrust produced controls the up and down motion of the submarine.

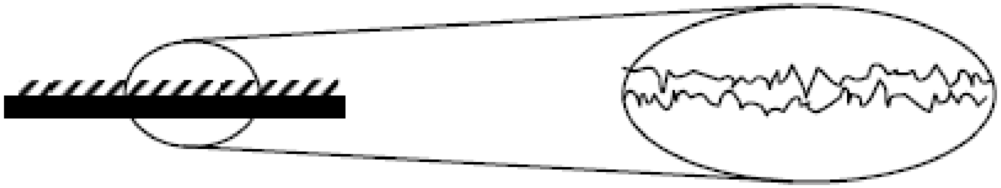
Frictional forces and Viscous forces

Frictional Forces

Frictional Forces

Friction is a force that opposes relative motion. It acts along the common surface in contact between the two bodies.

Frictional force arises in part from
(1) one peak physically blocking the motion of a peak from the opposing surface, even for surfaces which are apparently very smooth, as shown in the magnified view in Figure 8;
(2) chemical bonding of opposing points as they come into contact.



Two surfaces in contact

Magnified View

Frictional Forces (Continued)

Frictional forces are dissipative in nature as energy (which can otherwise be used to do useful work) is required to overcome them. This work done in overcoming friction is "wasted" in the form of thermal energy (heat) produced, which causes a rise in temperature. That is why your hands feel warm when rubbed together.

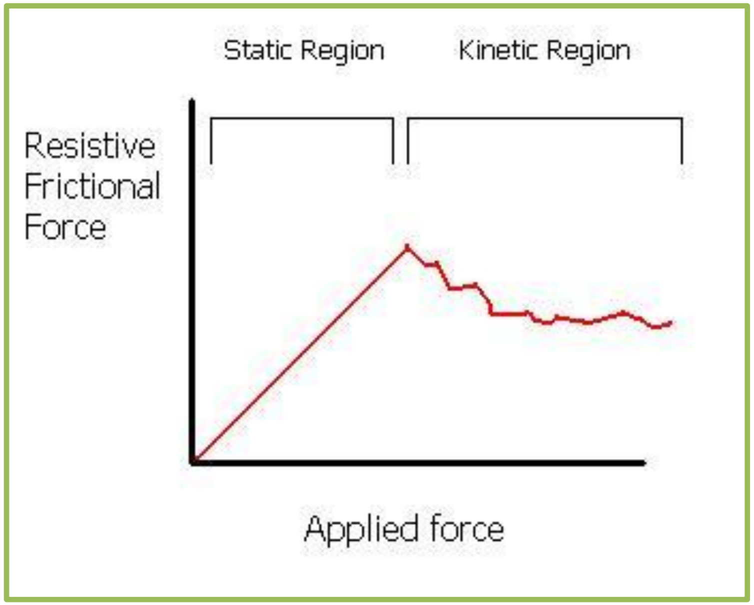
Note:

With all other factors kept constant,

1. a larger normal contact force will result in a larger frictional force (only for static friction).
2. the frictional force between any 2 surfaces in contact also depends on the nature of the surface (e.g. roughness of surface).
3. the frictional force between any 2 surfaces in contact is **independent of their contact area.**

Static Friction & Kinetic Friction

- There are two forms of friction, kinetic and static.
- If you try to slide two objects past each other, a small amount of force will result in no motion. The force of friction is greater than the applied force. This is static friction.
- If you apply a little more force, the object "breaks free" and slides, although you still need to apply force to keep the object sliding. This is kinetic friction. You do not need to apply quite as much force to keep the object sliding as you needed to originally break free of static friction.



Viscous Force

Viscous force (Friction in fluids)

It is the frictional force acting on a body when the body moves through a fluid i.e. a liquid or gas and dissipative in nature. Examples of viscous force is air resistance acting on a moving car and object falling in air.

Viscous force arises in fluids because there are attractive forces between fluid molecules.

Viscous force increases proportionally with speed in laminar flow conditions (when each particle of the fluid follows a smooth path and the paths of each particle do not cross each other).

Above a critical speed, the fluid flow becomes irregular and turbulent and viscous force increases proportionally with the square of speed.

Comparison between Frictional Forces and Viscous Forces

	Frictional Forces	Viscous Forces
Similarities	Dissipative in nature	Dissipative in nature
	Occur due to the attractive forces between molecules.	Occur due to the attractive forces between molecules.
	Oppose motion	Oppose motion
Differences	Act along the surfaces in contact between two solid objects.	Act between a fluid and a solid/fluid.
	Not affected by relative speed between the two surfaces.	Increase with the relative speed between the two surfaces.
	Friction exists even when the object is at rest.	Does not exist when there is no relative motion.

Using a vector triangle to represent forces in Equilibrium

1) **Two forces in equilibrium**

Consider two forces acting on a crate is in equilibrium,

Conclusion:

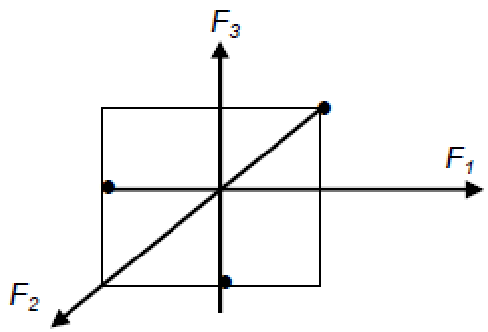
They must act along the same line of action (collinear), be equal in magnitude and opposite in direction.

$\Sigma F_x = 0$; $\quad F_1 - F_2 = 0$

$F_1 = F_2$ (no resultant force)

2) Three forces in equilibrium

Consider three forces acting on a crate is in equilibrium,

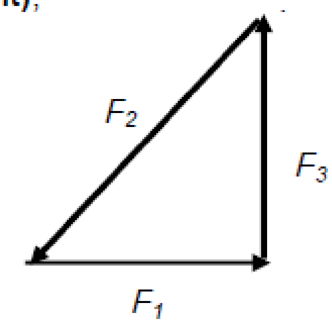


Conclusion:

1) They must act on the same plane (**coplanar**)

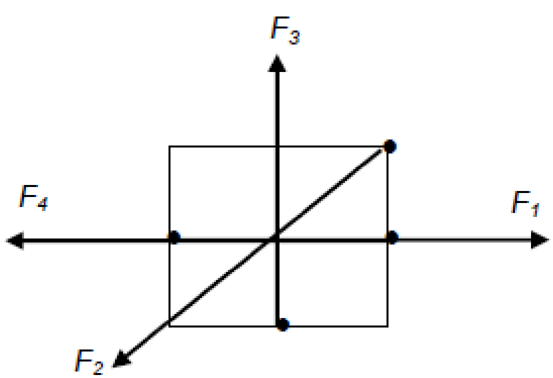
2) They form a **closed triangle**.

3) They must **all act through the same point (concurrent)**,



3) Four or more forces in equilibrium

Consider four or more forces acting on a crate is in equilibrium,

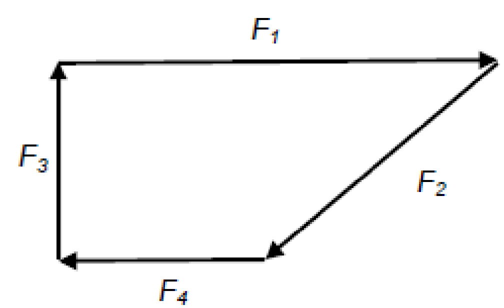


Conclusion:

1) They must act on the same plane (coplanar)

2) They form a closed polygon

3) They must all act through the same point.



Centre of Gravity

- The weight of an object may be taken as acting at one point known as the centre of gravity.
- You could think of that point as the position where all the mass of the object could be thought to be concentrated.

The **centre of gravity** of an object is the point through which the weight of the object is taken to act.

The weights *w* of *n* individual particles of an object are effectively parallel to each other as seen in Figure in 9(a).

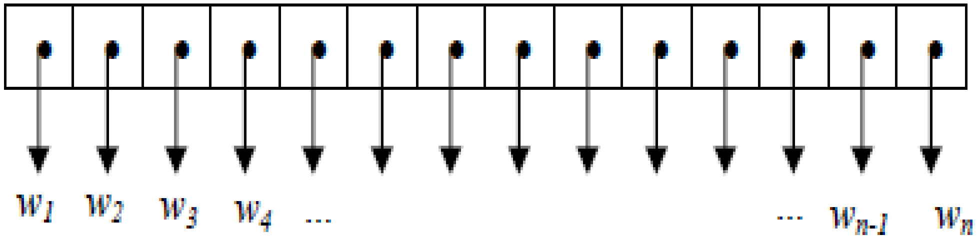


Figure 9(a)

The weight *W* of an object is the resultant force of all the individual weights *w* of its particles in the object and is directed towards the centre of the Earth. The centre of gravity, *G* of a rigid body (Figure 9b) is the single point through which the weight of the object appears to act.

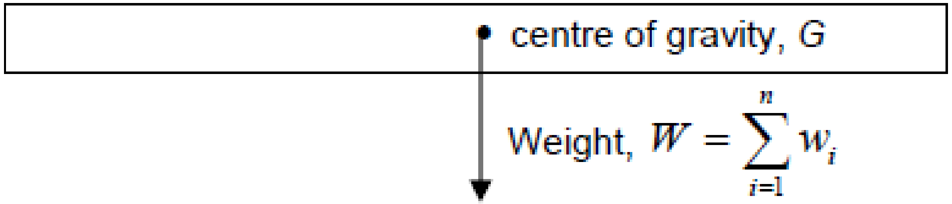


Figure 9(b)

The factors affecting position of centre of gravity are (1) distribution of the masses; and (2) the acceleration of free fall *g*.

Hence, if the distribution of masses and *g* remain constant on all parts of the objects, the centre of gravity will coincide with the centre of mass of the object.

A couple

- In physics, couple is a pair of equal parallel forces that are opposite in direction. Couples produce or prevent the turning of a body.

- The forces used to turn the steering wheel of a car constitute a couple; each hand exerts a force, parallel but opposite in direction, yet they work together to achieve the same goal.

- It tends to produce rotation only. There is no linear change in motion due to net/resultant force being zero. The pair of forces is non-concurrent. (i.e. their lines of actions do not pass through the a single common point)

The moment of a Force

- The moment of a force about a pivot is the product of that force and the perpendicular distance between the line of action of the force and the pivot.

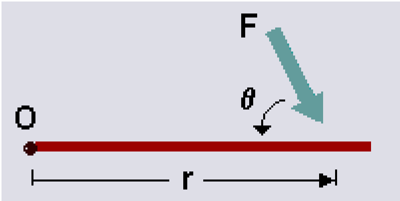
Moment of a force (calculation)

- The moment of a force can be worked out using the formula:
- Moment = force applied × perpendicular distance from the pivot.
- If the magnitude of the force is F Newtons and the perpendicular distance is d metres then:

  Moment = Fd

The Torque of a couple

- When a driver turns a steering wheel, he exerts two equal but opposite forces on it. The two forces form a couple. The turning effect of a couple is the sum of moment of the two forces. The moment of a couple is called a torque.

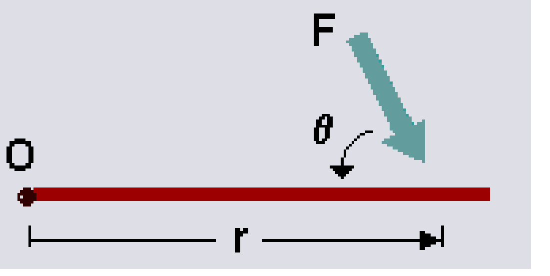


- The torque of a couple is the

product of one of the forces and the perpendicular distance between their lines of action.

In other words, Torque is...

- ***Torque* is a measure of how much a force acting on an object causes that object to rotate.**



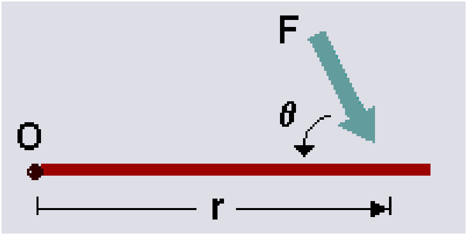
- The object rotates about an axis,

which we will call the **pivot point**, and will label 'O'.

- We will call the force '**F**'. The distance from the pivot point to the point where the force acts is called the **moment arm**, and is denoted by '**r**'. Note that this distance, '**r**', is also a vector, and points from the axis of rotation to the point where the force acts. (Refer to Figure for a pictorial representation of these definitions.)

Calculation of Torque

- Torque is calculated using the equation
  τ = **r** x **F** = **r F** sinθ.



- In other words, torque is the cross product between the distance vector (the distance from the pivot point to the point where force is applied) and the force vector, 'a' being the angle between **r** and **F**.
- Using the **right hand rule**, we can find the direction of the torque vector. If we put our fingers in the direction of **r**, and curl them to the direction of **F**, then the thumb points in the direction of the torque vector.

When there is no resultant force and no resultant torque, a system is in equilibrium

A system is in equilibrium

- The state of a body or physical system that is at rest or in constant and unchanging motion.
- If a system is in **static equilibrium**, there are no net forces and no net torque in the system.
- If a system is in **stable equilibrium**, small disturbances to the system cause only a temporary change before it returns to its original state.

Two conditions must be satisfied for static equilibrium to take place for a **<u>rigid body.</u>**

(1)	The **resultant force** acting on the object is **zero**.
(2)	The **resultant torque** acting on the object is **zero**.

a) **Resultant force = zero**

The vector sum of all external forces acting on a rigid body must be zero i.e. no net/resultant force

$$\boxed{\Sigma F = 0}$$

b) **Resultant torque = zero**

The vector sum of all external torques acting on a rigid body must be zero i.e. No net/resultant torque, OR

Mathematically,

$$\boxed{\Sigma \tau = 0}$$

Principle of moments

State the Principle of Moments

If a body is in equilibrium the sum of the clockwise moments is equal to the sum of the anticlockwise moments.

Principle of moments for a body in equilibrium

An object is in equilibrium if the sum of all anticlockwise moments about the pivot is equal to the sum of all clockwise moments about the same pivot.

All anti-clockwise moments can be taken to be positive and clockwise moments to be negative or vice versa.

Density and Pressure

- Density is defined as the mass per unit volume of a substance:

  $$\text{density} = \frac{\text{mass}}{\text{volume}}$$

- Pressure is defined as the normal force acting per unit cross-sectional area:

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

- Pressure in a fluid increases with depth:

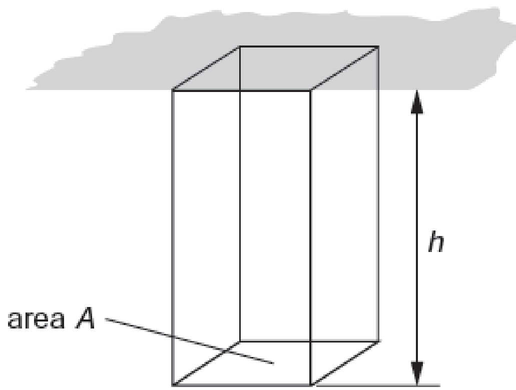
  $$p = \rho g h$$

Derive from the definitions of pressure and density, the equation $p = \rho gh$

It is a well-known fact that pressure increases with depth of liquid. The relation between the pressure p due to a fluid (liquid or gas) at depth h is given by the equation

$$p = \rho gh,$$

where ρ is the density of the fluid and g is the acceleration of free fall. The equation can be derived as follows:



Consider a flat horizontal surface at a depth h in a fluid of density ρ. Then,

$$\begin{aligned} \text{mass of fluid on area} &= \text{density x volume} \\ &= \rho Ah \\ \text{and weight of fluid on area} &= \rho Ahg. \end{aligned}$$

This weight of fluid produces a pressure p on the area given by

$$\begin{aligned} \text{pressure } p &= \frac{\text{force}}{\text{area}} \\ &= \frac{\rho gAh}{A} \\ p &= \rho gh. \end{aligned}$$

Note that this equation allows the pressure due to the fluid to be calculated. It should be remembered that the actual pressure at depth h in a liquid would be given by

$$\text{pressure} = \rho gh + \text{atmospheric pressure at liquid surface}$$

Sample problem 1

- Calculate the pressure on an inspection harch 7m diameter located on the bottom of a tank when it is filled with oil of density 875 Kgm^{-3} to a depth of 7 metres.

Solution

The Pressure at the bottom of the tank is given by $p = \rho gh$

ρ = 875 Kgm^{-3} , h = 7m, g = 9.8ms^{-2}

$p = \rho gh$

= 875 x 9.8 x 7

= 60.086 kPa