2 FORCES & MOMENTS

H2 Physics 9478

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Learning Outcomes

Candidates should be able to:

(a) describe the forces on a mass, charge and current-carrying conductor in gravitational, electric and magnetic fields, as appropriate.

(b) show a qualitative understanding of forces including normal force, frictional force, buoyant force (upthrust), and viscous force, e.g. air resistance (knowledge of the concepts of coefficients of friction and viscosity is not required). **[Buoyant force (upthrust) not in H1 syllabus]**

(c) recall and apply Hooke's law ($F = kx$, where k is the force constant) to new situations or to solve related problems.

(d) define and apply the moment of a force and the torque of a couple.

(e) show an understanding that a couple is a pair of forces which tends to produce rotation only.

(f) show an understanding that the weight of a body may be taken as acting at a single point known as its centre of gravity.

(g) apply the principle of moments to new situations or to solve related problems.

(h) show an understanding that, when there is no resultant force and no resultant torque, a system is in equilibrium.

(i) use free-body diagrams and vector triangles to represent forces on bodies that are in rotational and translational equilibrium.

2.1 Type of Forces

To date, physicists recognize four fundamental forces in nature:

1. The gravitational force
2. The electromagnetic force
3. The strong nuclear force (not in syllabus)
4. The weak (nuclear) force

All other forces we know can be derived from these four fundamental forces. Other than the gravitational force, most forces such as pushes, pulls and other contact forces like the normal reaction force and friction, are due to the electromagnetic force acting at the atomic level.

In the H2 Physics syllabus, you will learn that a mass experiences a gravitational force in a gravitational field, a charge experiences an electric force in an electric field and a current carrying conductor experiences a magnetic force in a magnetic field. These forces will be covered in later topics.

❖ Weight and Centre of Gravity

For a body near the surface of the Earth, its weight *W*, is defined as the force experienced by a body of mass *m* in a gravitational field and can be expressed as

$$W = mg$$

where *g* is the gravitational field strength.

This force acts vertically downwards towards the centre of the Earth through a single point on or outside the body known as its centre of gravity (C.G.).

The dot at the centre of the body is its centre of gravity.

Fig. 2.1

Definition
The **centre of gravity** of a body is the point at which the weight of the body (or the resultant of the distributed gravitational attraction on the body) appears to act.

❖ Normal force

The normal contact force *N* is the force exerted on a body when it is in contact with a surface. The normal contact force is always perpendicular to the contact surface and points away from that surface.

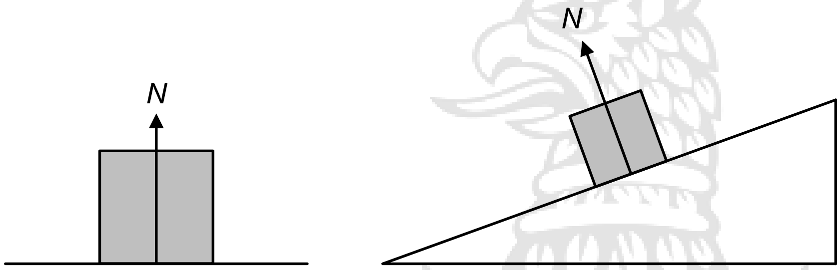


Fig. 2.2

❖ Buoyant force (Upthrust) [not in H1 syllabus]

Upthrust *U* is the vertical upward force exerted on a body by a fluid when it is fully or partially submerged in the fluid due to the difference in fluid pressure.

It can be shown to be equal in magnitude and opposite in direction to the weight *W* of the fluid displaced by a submerged or floating object.

Do not confuse upthrust with thrust. **Thrust** can be described as a force that is exerted on an object by the expulsion or acceleration of mass in one direction.

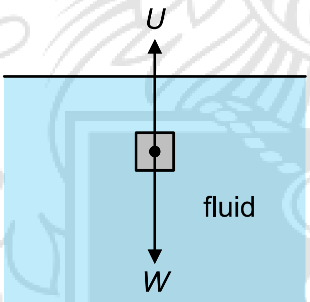


Fig. 2.3

If the upthrust is greater than the weight of the object, the object will accelerate up (float), otherwise it will accelerate downwards (sink).

❖ Frictional force

Friction is the force that acts to oppose the relative motion or tendency of relative motion between two surfaces in contact. It acts parallel to the two surfaces in contact.

Friction enables a person to walk on a path or to hold an object securely without dropping. Friction also allows wheels to rotate without slipping.

On the other hand, friction causes wear and tear in mechanical system and produces excess heat that may cause damage to system.

- **Examples of friction:**
- Static friction
- Sliding / kinetic friction
- Rolling friction - resistance produced when a rolling body moves over a surface
- Viscous forces or fluid friction - the friction between moving fluids or between fluids and solids

❖ Viscous force

Viscous force arises when an object moves through a fluid, it imparts momentum to the fluid molecules, hence causing itself to slow down.

Does a viscous liquid necessarily have a large density?

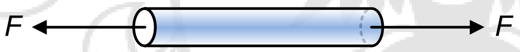
Air resistance is one commonly experienced viscous force as objects move through air.

Viscous force depends on:

- the shape of the body,
- the speed of the body, and
- the viscosity of the fluid.

❖ Tension and Compression

When an object such as a bar (or rod or wire) is pulled at its ends, we say a force ***F*** is pulling on the bar, and the magnitude of the force is called the tension in the bar, often denoted by *T*.



bar in tension

When the object (e.g. a rigid rod) is pushed on both ends, we say that the object is in compression.

bar in compression

We often deal with springs, strings or ropes that are in tension, i.e., experiencing a pulling force.

❖ **Summary of Forces**

Force	**Direction**
Weight	Acts vertically downwards towards the centre of Earth through an object's centre of gravity (c.g.).
Normal contact force	Always perpendicular to the surfaces in contact.
Frictional force	Always opposite to the tendency or direction of motion, and parallel to the two surfaces in contact.
Tension	When forces are directed away from the object affected along the object.
Compression	When forces are directed towards the object affected along the object.
Upthrust	Vertical upward force exerted by a fluid on a body submerged fully or partially in the fluid.
Viscous force	Always opposite to the direction of relative motion of the object moving in a fluid.

❖ Hooke's Law

Consider a spring suspended from the ceiling. It has an extension x when a force F is applied to it.

To investigate Hooke's law, a graph of applied force F against the spring extension x, is plotted.

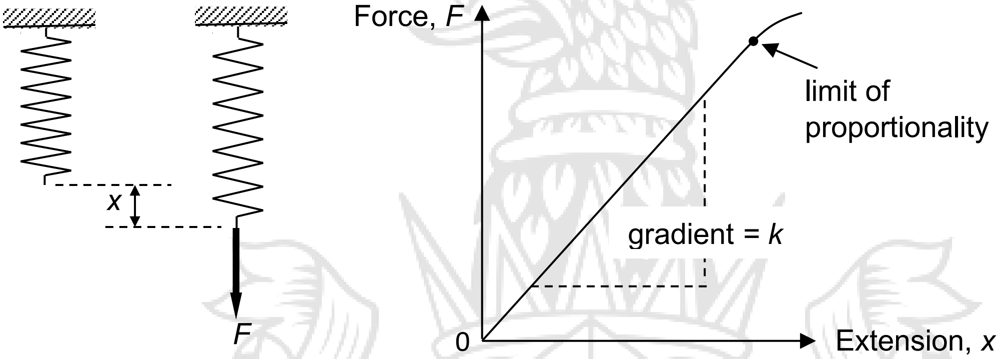


Fig. 2.4

Definition
Hooke's Law states that the extension of a body is proportional to the applied load if the limit of proportionality is not exceeded.

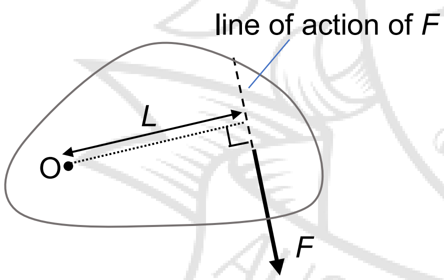
$F = kx$ where k is the force (or spring) constant

2.2 Moment and torque

❖ Moment

The turning effect of a force is called the moment of the force.

Consider a force F acting on a rigid body in the plane of the paper so as to cause it to turn about an axis perpendicular to the paper, with pivot at O on the same plane as shown in Fig. 2.5.



Moment τ of the force = $L \times F$
Units of moment: N m

Fig. 2.5

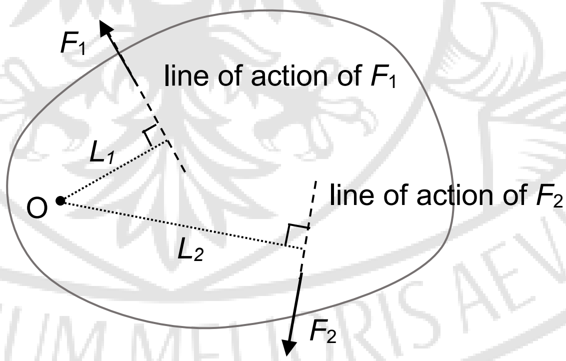


Fig. 2.6

In Fig. 2.6, a rigid body is acted on by forces F_1 and F_2 lying in the plane of the paper.

F_1 would produce a counter-clockwise rotation, whilst F_2 a clockwise rotation about O.

If we take clockwise moment as positive, anticlockwise moment would be negative.

The net moment of the two forces about O is therefore given by

$$\tau = F_2L_2 - F_1L_1$$

> **Definition**
>
> The **moment** of a force about an axis is defined as the product of the force and the perpendicular distance of the line of action of the force from the axis.

❖ **Torque of a Couple**

A couple is a pair of forces which tends to produce rotation only.

> **Definition**
>
> A **couple** consists of a pair of **equal** and **opposite** forces whose lines of action do not coincide.

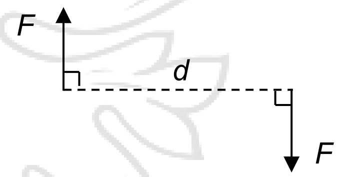


Fig. 2.7

Torque of couple $= Fd$

> **Definition**
>
> **Torque of a couple** is the product of the magnitude of one of the forces and the perpendicular distance between the forces.

Note:

A body acted on by a couple has zero resultant force and the body is in translational equilibrium. However, the couple will produce a turning effect hence the body is **NOT** in rotational equilibrium.

2.3 Translational and rotational equilibrium

❖ Body in equilibrium

For a body to be in equilibrium, it must be in both <u>translational</u> and <u>rotational</u> equilibrium.

These are the two conditions necessary for a body to be in **equilibrium**,

1. The resultant force on the body is zero.
2. The resultant moment on the body about any axis is zero.

❖ Translational equilibrium

For a body to be in **translational equilibrium**, the resultant force (vector sum of the forces) acting on it must be zero.

Consider a particle that is subject to two forces, F_1 and F_2.

- The particle will move in the direction of the resultant of F_1 and F_2.
- The resultant force on the particle is zero only if F_1 and F_2 are equal in magnitude and opposite in direction.

Now consider 3 coplanar forces, F_1, F_2 and F_3 acting on a particle A as shown in Fig. 2.8 (a).

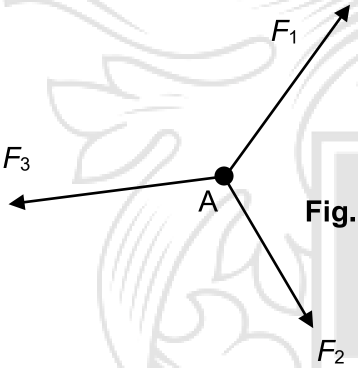


Fig. 2.8 (a)

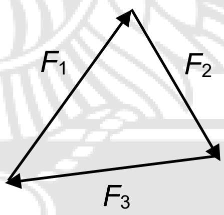


Fig. 2.8 (b)

If the resultant force is zero, the vector sum of the three forces must be zero.
The vector diagram of the three forces will be a closed triangle in one direction (see Fig. 2.8 (b)).

For a particle subject to more than three forces, this same principle applies.
By drawing a polygon of forces, it will form a closed polygon in one direction.

Another method used to solve problems associated with objects in translational equilibrium:

- resolve all forces into two perpendicular components
- equating the sum of components in each direction to zero. i.e. $\sum F_x = 0$ and $\sum F_y = 0$.

❖ Rotational equilibrium

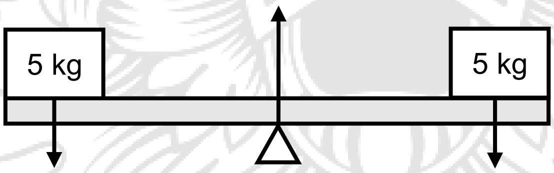
For a body to be in **rotational equilibrium**, the resultant moment on the body about any axis is zero. The principle of moments must be satisfied.

> **Definition**
>
> **Principle of Moments** :
>
> For a body in equilibrium, the sum of all the clockwise moments about any axis must equal the sum of all the anticlockwise moments about the same axis.

When only three coplanar forces act on a body in equilibrium, their lines of action must either
(i) all be parallel or
(ii) all meet at a point.

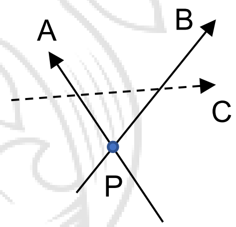
Scenario 1 (parallel forces)

Horizontal beam in equilibrium.



Scenario 2 (non-parallel forces)

Since the object is in rotational equilibrium, when taking moments about any axis, net moment should always be zero.



Why is this so?

When three coplanar forces act on an object, the lines of action of any two forces (e.g. A and B, non-parallel) must certainly meet at a point (e.g. P).

If the line of action of the third force C does not meet at the same point P, force C will cause a moment about point P and the object cannot be in rotational equilibrium.

Hence, for object to be in equilibrium, the lines of action of all three forces must meet at a point.

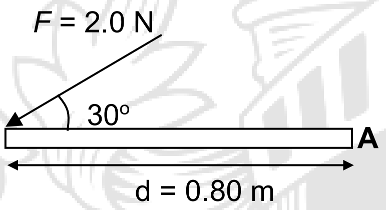
Example 1

A load of 50 N is suspended from a spring with a force constant of 1000 N m^{-1}. Calculate the extension of the spring.

Energy stored in a spring will be discussed in Topic 4.

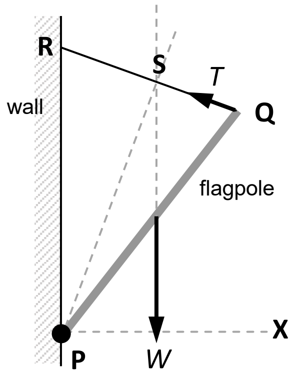
Example 2

A force F is applied to a rod. Calculate the moment of F about the end A of the rod.



Example 3

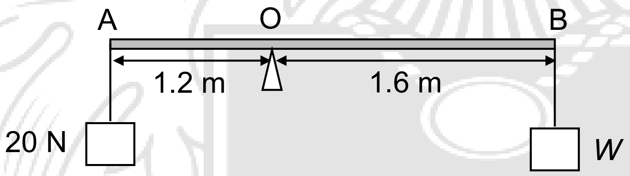
The diagram shows a heavy flagpole PQ hinged at a vertical wall at end P and held by a wire connected between end Q and a point R on the wall. The weight of the flagpole is *W* and the tension in the wire is *T*.



What is the direction of the force *F* exerted by the wall on the flagpole?
(A) PQ **(B)** PS **(C)** PX **(D)** QP **(E)** SP

Example 4

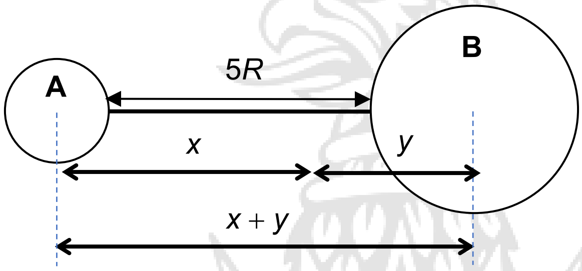
A rigid rod of negligible weight is pivoted at point O and carries a block of weight 20 N at end A.



Calculate
(i) the weight *W* of a second block that must be attached at end B if the rod is to be in equilibrium, and
(ii) the force *P* exerted on the rod by the pivot at O.

Example 5

Two spheres A and B of the same material and of radius R and $2R$ respectively are joined together by a light rod of length $5R$. Assuming that the system of spheres is in a uniform gravitational field, determine the distance of the c.g. from the centre of sphere B.



2.4 Appendix

❖ Static Friction (not in Syllabus)

Consider a block resting on a rough surface. Apply a small horizontal force F to the right.

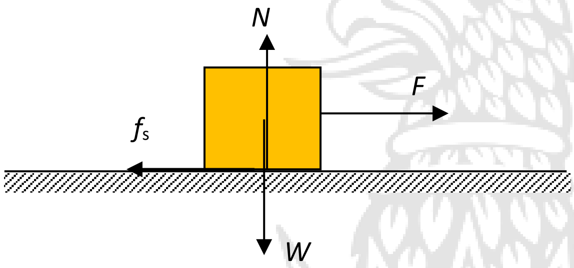


Fig. 2.9

If the block remains at rest, static friction $f_s = F$ (Newton's 1st Law).

If F is increased and the block remains at rest, f_s increases.

Eventually when F becomes large enough, the block begins to slide. Thus there exists a maximum possible static friction force $f_{s,max}$ which we call the *limiting frictional force*.

Experimentally, $f_{s,max}$ has the following properties:

1. $f_{s,max}$ is independent of the surface area that is in contact.
2. For a given pair of surfaces, $f_{s,max} \propto N$. Hence $f_{s,max} = \mu_s N$ where μ_s is called the coefficient of static friction.
3. μ_s depends on the nature of the two surfaces.

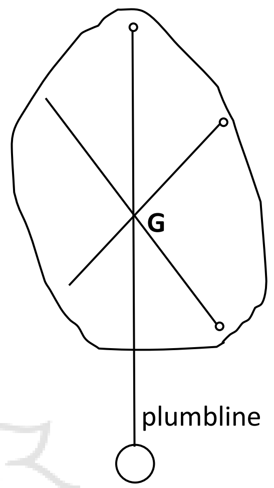
□

❖ Kinetic Friction (not in Syllabus)

The force necessary to keep an object sliding at constant velocity is smaller than that required to start it moving. Hence the sliding or kinetic friction force f_k is less than $f_{s,max}$. It is independent of the contact area and it satisfies $f_k = \mu_k N$ where μ_k is called the coefficient of kinetic friction. μ_k is nearly independent of velocity and $\mu_k < \mu_s$.

❖ Experimental Determination of Centre of Gravity

A procedure to find the C.G. of a lamina is as follows:



1. Make 3 small holes at well-spaced intervals round the edge of the lamina.
2. A pin is put through one of the holes and held firmly by a clamp and stand so that the lamina can swing freely. The lamina will come to rest with its centre of gravity, G, vertically below the point of support. The vertical line through the support can now be located by means of a plumbline. A plumbline is hung from the pin and the position of the thread marked on the lamina by two small pencil crosses. These crosses are joined by a pencil line.
3. Repeat Step 2 for the other two holes. Trace out the 3 lines and they should all intersect at G.