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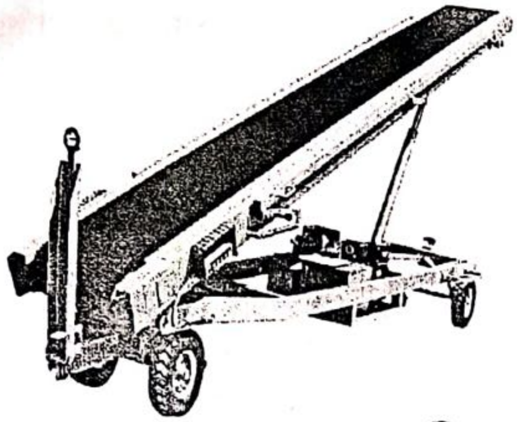
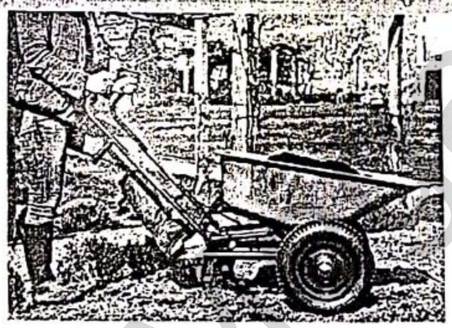
CHAPTER 5:
TURNING EFFECT OF FORCES





Syllabus Content

5.1 Moments
5.2 Centre of mass
5.3 Stability

Learning outcomes

Candidates should be able to:

(a) Describe the moment of a force in terms of its turning effect and relate this to everyday examples.

(b) State the principle of moments for a body in equilibrium.

(c) Define *moment of a force* and recall and use the formula *moment = force × perpendicular distance from the pivot* and the principle of moments.

(d) Describe how to verify the principle of moments.

(e) Describe how to determine the position of the centre of mass of a plane lamina.

(f) Describe qualitatively the effect of the position of the centre of mass on the stability of simple objects.

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Turning Effect of Forces

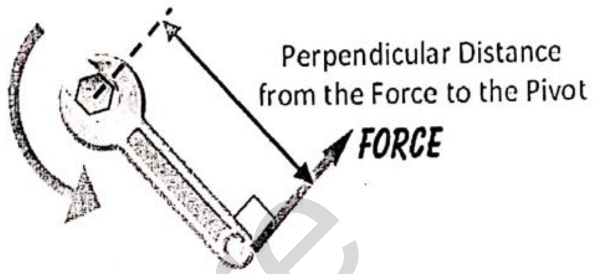
If a body is fixed at a certain point (called pivot or fulcrum), a force applied to the body cannot displace it, but rather it can turn it about the pivot. The turning effect of a force is called the moment of the force and it depends both on the size of force and its distance from the pivot.

Thus the moment of a force about a point

= force × perpendicular distance

Moment = $F \times d_{perp}$.

Measured in N. m.

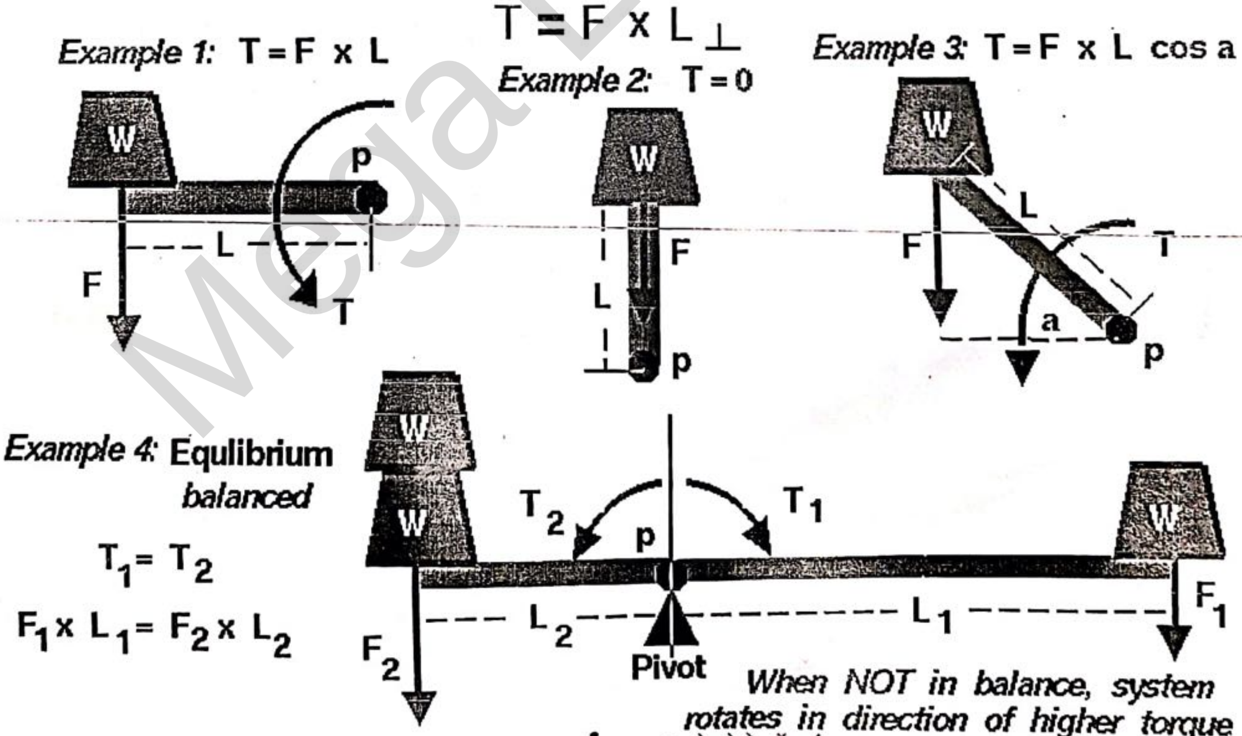


The moment of the force is its turning effect on the body about a fixed point. Moment is the product of force and its perpendicular distance from the pivot.

Clockwise moment is considered negative (-), and anticlockwise moment is considered positive (+).

The Torque (T) about a point (p) is equal to the Force (F) times the distance (L) measured perpendicular to the force.

$$T = F \times L_{\perp}$$



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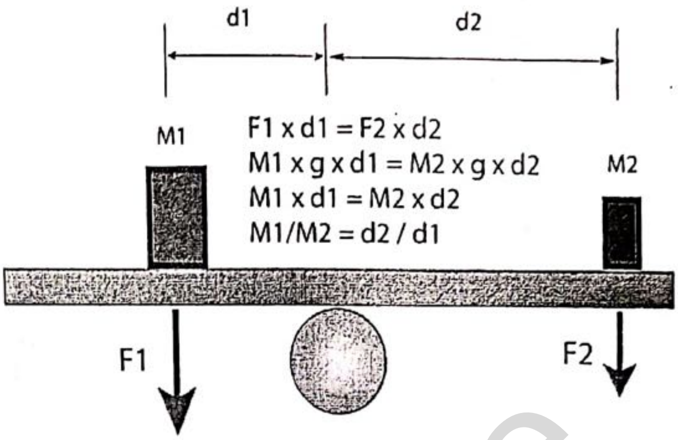
Conditions for Equilibrium:

If a body is in equilibrium under the action of several parallel forces, it must satisfy two conditions:

1. The sum of the forces in one direction must equal the sum of the forces in the opposite direction.
2. The principle of moments must apply. It states that "the sum of anticlockwise moments about any point is equal to the sum of the clockwise moments about that point".

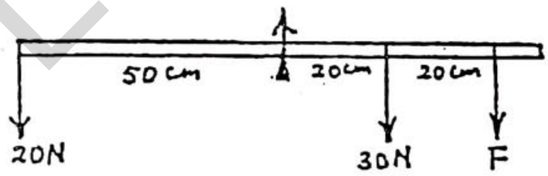


In equilibrium, for a simple case we use that

$$F_1 \times d_1 = F_2 \times d_2$$

If there is no equilibrium, i.e., there is a resultant moment different from zero; the resultant moment produces rotation of the system.

Example: A uniform meter rule is pivoted at its center and is balanced under the forces shown. Find the force F and calculate the value of the force at the pivot.



Solution:

Sum of clockwise moments = Sum of anticlockwise moments

(30 x 20) + (F x 40) = (20 x 50)

40 F = 1000 – 600

F = 10 N

The force at the pivot = 20 + 30 + 10

= 60N upwards

Experiment: To verify the Principle of Moments:

1. Support a meter rule with a hole drilled at its center on a string tied to rigid support. If the rule does not balance horizontally add a small piece of plasticize to the raised end to level it.
2. Position a weight W_1 tied to a loop of thread on the left of rule (to an accuracy of 1 mm).

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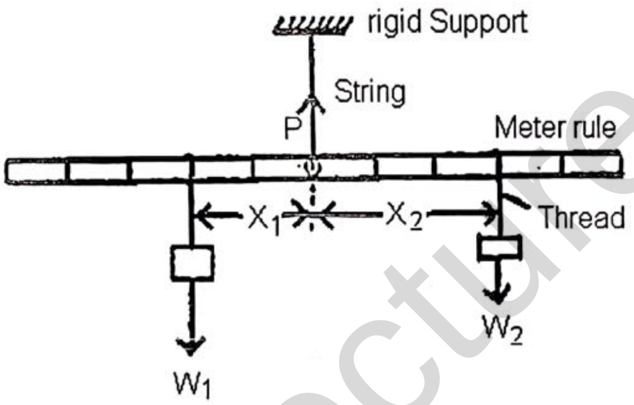
3. Hang a second weight W_2 on the right of P and move its loop until the rule is balanced horizontally.
4. Read and record the distances X_1 and X_2 from the meter rule itself.
5. Move the weights W_1 and W_2 to other positions and record the results as before and repeat this several times.
6. Calculate $W_1 X_1$ and $W_2 X_2$ (in N.cm) to show that they are numerically equal (within the limits of experimental error).



W_1 (N)	X_1 (cm)	$W_1 X_1$ (N.cm)	W_2 (N)	X_2 (cm)	$W_2 X_2$ (N.cm)

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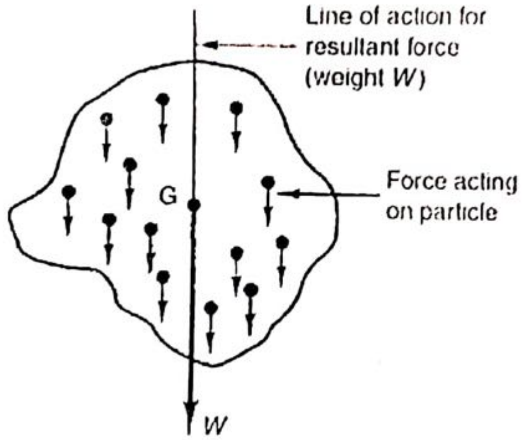
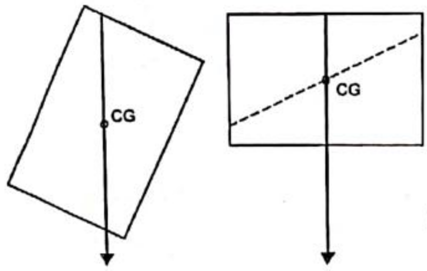
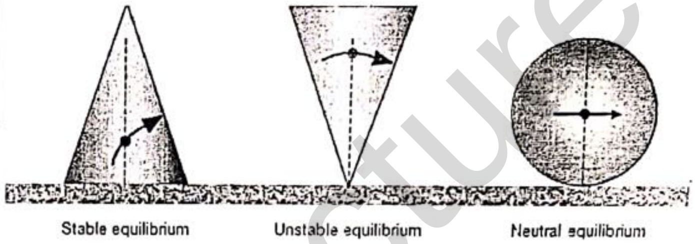
Centre of Gravity

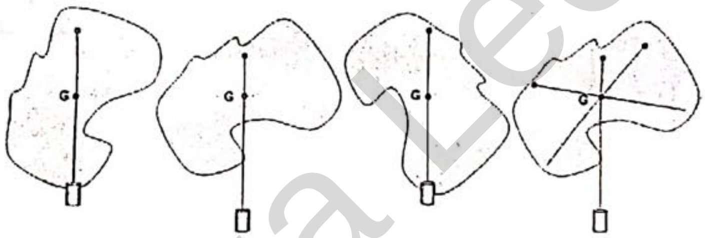
Centre of Gravity e.g., of a body is the point of application of the resultant force due to earth's attraction. The weight of a body acts through its center of gravity. For a regular and uniform body, c.g. lies on its geometrical center.



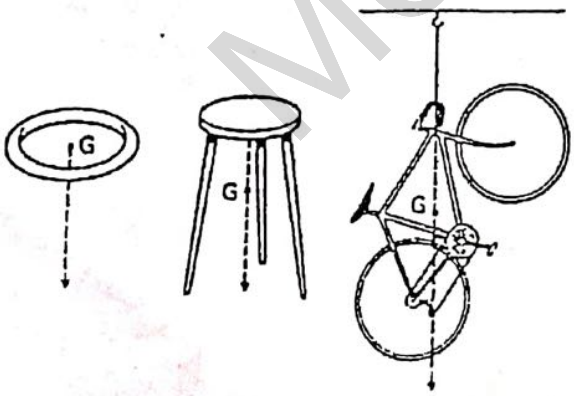
For an irregular sheet, it could be hanged together with a plumb line to determine the vertical direction. The intersection of few vertical lines (from different points of suspension) determines the center of gravity.

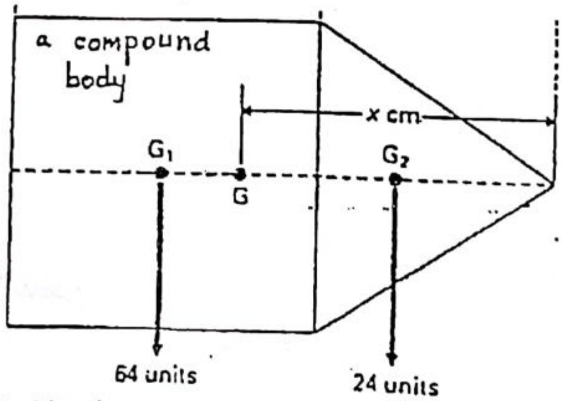






Centre of gravity can also be located by balancing the sheet on a straight edge several directions.





Centre of gravity of a compound body is displaced towards the heavier part.

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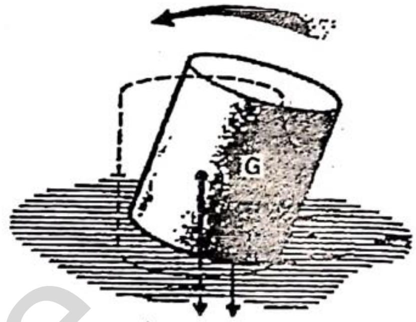
Stability:

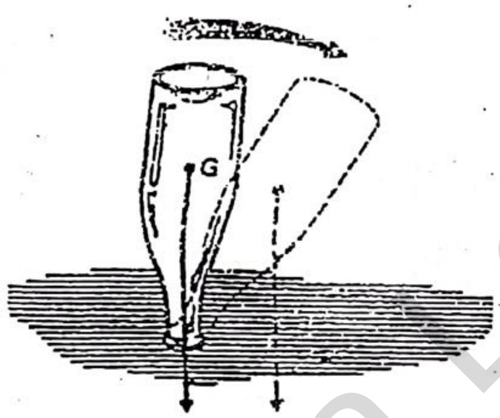
Stable Equilibrium: A body is in stable equilibrium when it returns to its original position after being given a small displacement. (the moment produced by its weight returns it back to its original position).

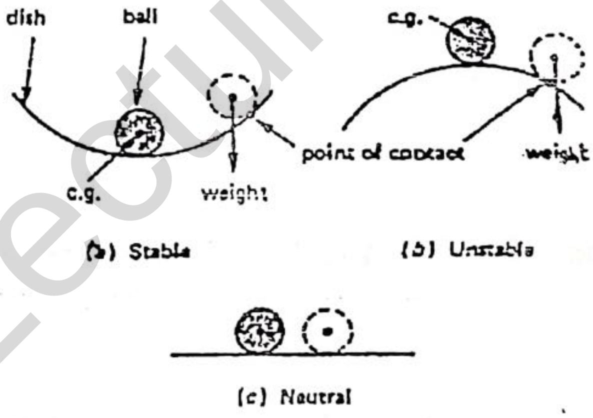
Stability of a body increases by:

1. Having large base area.
2. Having low center of gravity.



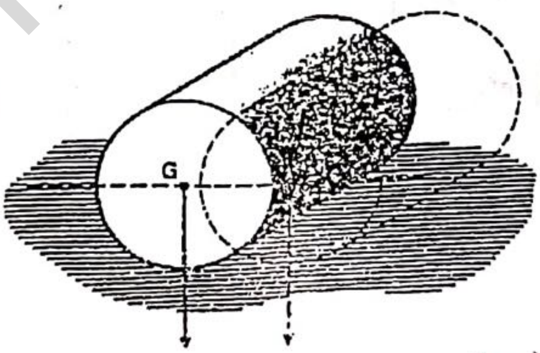
Unstable equilibrium occurs when a small displacement of the body produces a moment which causes the body to fall down. (case of bottle standing on its neck).





If the vertical line of the weight vector passes out of the base area, the body will fall down.

Neutral Equilibrium occurs when the weight vector always passes through the point of contact with the surface, there is no moment produced. When the body is displaced, it always rests at the new position. (case of a ball lying on a plane surface).



'Kelly doll'

A self-righting toy

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Equilibrium

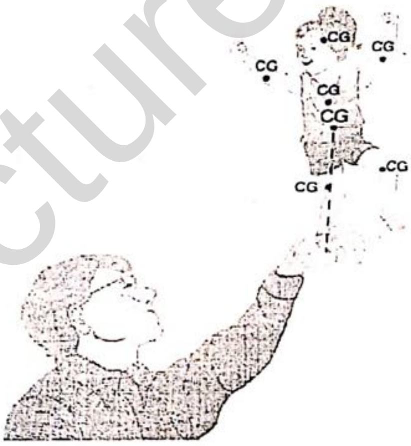
Types of Equilibrium

- State the types of equilibrium.
- Describe stable and unstable equilibriums.
- Describe neutral equilibrium.

It is one thing to have a system in equilibrium; it is quite another for it to be stable. The toy doll perched on the man's hand in Figure 1, for example, is not in stable equilibrium. There are *three types of equilibrium*: *stable*, *unstable*, and *neutral*. Figures throughout this module illustrate various examples.

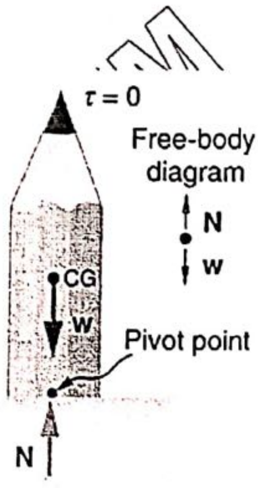
Figure 1 presents a balanced system, such as the toy doll on the man's hand, which has its center of gravity (cg) directly over the pivot, so that the torque of the total weight is zero. This is equivalent to having the torques of the individual parts balanced about the pivot point, in this case the hand. The cgs of the arms, legs, head, and torso are labeled with smaller type.

A system is said to be in *stable equilibrium* if, when displaced from equilibrium, it experiences a net force or torque in a direction opposite to the direction of the displacement. For example, a marble at the bottom of a bowl will experience a *restoring* force when displaced from its equilibrium position. This force moves it back toward the equilibrium position. Most systems are in stable equilibrium, especially for small displacements. For another example of stable equilibrium, see the pencil in Figure 2.



A man balances a toy doll on one hand.

A system is in *unstable equilibrium* if, when displaced, it experiences a net force or torque in the *same* direction as the displacement from equilibrium. A system in unstable equilibrium accelerates away from its equilibrium position if displaced even slightly. An obvious example is a ball resting on top of a hill. Once displaced, it accelerates away from the crest. See the next several figures for examples of unstable equilibrium.



This pencil is in the condition of equilibrium. The net force on the pencil is zero and the total torque about any pivot is zero.

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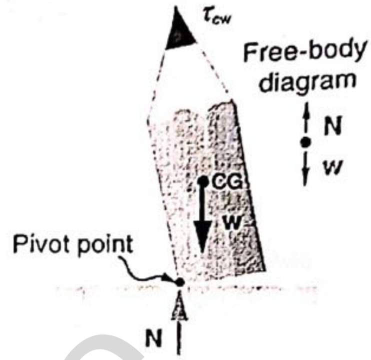
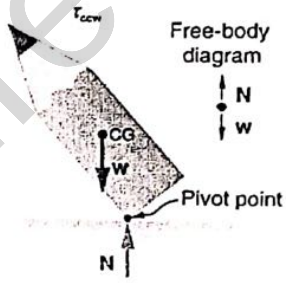
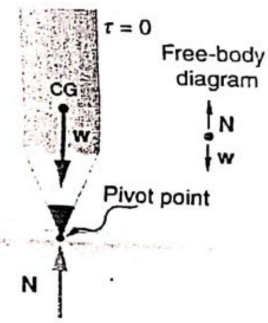
If the pencil is displaced slightly to the side (counterclockwise), it is no longer in equilibrium. Its weight produces a clockwise torque that returns the pencil to its equilibrium position.



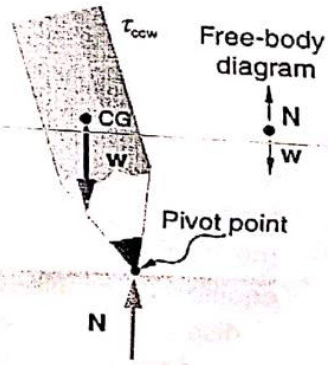
If the pencil is displaced too far, the torque caused by its weight changes direction to counterclockwise and causes the displacement to increase.



This figure shows unstable equilibrium, although both conditions for equilibrium are satisfied.



If the pencil is displaced even slightly, a torque is created by its weight that is in the same direction as the displacement, causing the displacement to increase.



A system is in *neutral equilibrium* if its equilibrium is independent of displacements from its original position. A marble on a flat horizontal surface is an example. Combinations of these situations are possible. For example, a marble on a saddle is stable for displacements toward the front or back of the saddle and unstable for displacements to the side. Figure 6 shows another example of neutral equilibrium.

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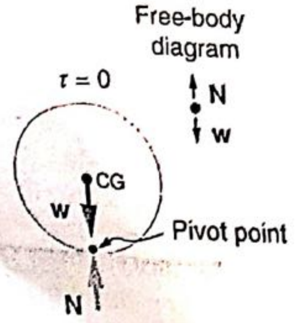
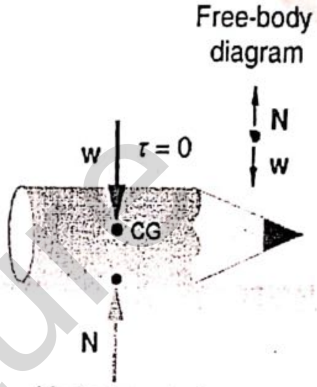
(a) Here we see neutral equilibrium. The cg of a sphere on a flat surface lies directly above the point of support, independent of the position on the surface. The sphere is therefore in equilibrium in any location, and if displaced, it will remain put. (b) Because it has a circular cross section, the pencil is in neutral equilibrium for displacements perpendicular to its length.

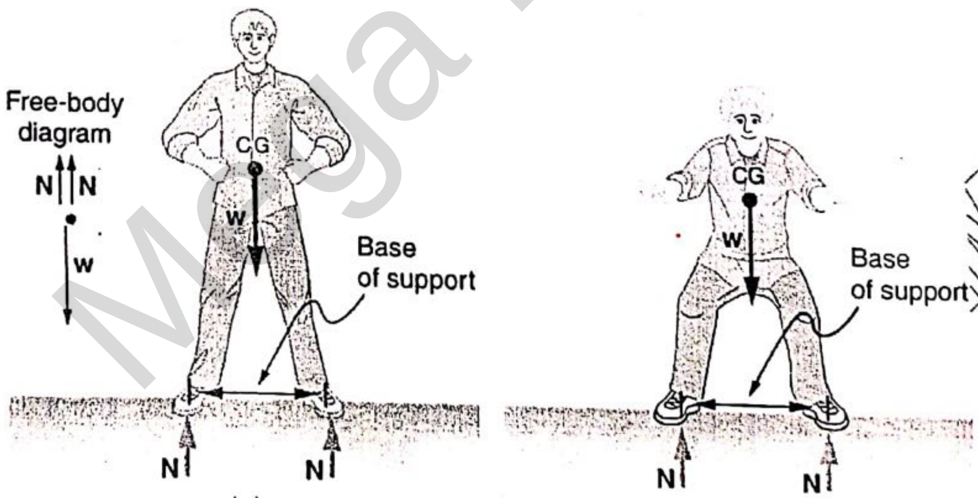


Neutral
(a)



Limited neutral
(b)

When we consider how far a system in stable equilibrium can be displaced before it becomes unstable, we find that some systems in stable equilibrium are more stable than others. The pencil in Figure 2 and the person in Figure 8(a) are in stable equilibrium, but become unstable for relatively small displacements to the side. The critical point is reached when the cg is no longer *above* the base of support. Additionally, since the cg of a person's body is above the pivots in the hips, displacements must be quickly controlled. This control is a central nervous system function that is developed when we learn to hold our bodies erect as infants. For increased stability while standing, the feet should be spread apart, giving a larger base of support. Stability is also increased by lowering one's center of gravity by bending the knees, as when a football player prepares to receive a ball or braces themselves for a tackle. A cane, a crutch, or a walker increases the stability of the user, even more as the base of support widens. Usually, the cg of a female is lower (closer to the ground) than a male. Young children have their center of gravity between their shoulders, which increases the challenge of learning to walk.



(a) (b)

(a) the center of gravity of an adult is above the hip joints (one of the main pivots in the body) and lies between two narrowly-separated feet. Like a pencil standing on its eraser, this person is in stable equilibrium in relation to sideways displacements, but relatively small displacements take his cg outside the base of support and make him unstable. Humans are less stable relative to forward and backward displacements because the feet are not very long. Muscles are used extensively to balance the body in the front-to-back direction. (b)

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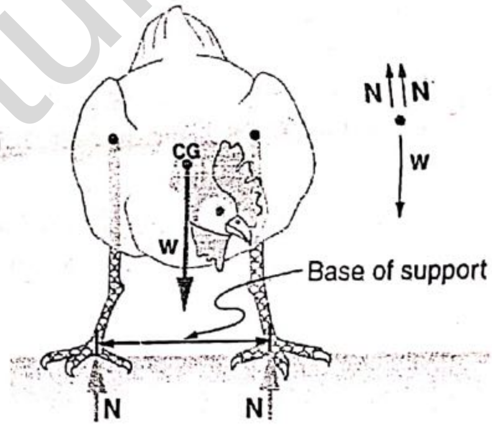
While bending in the manner shown, stability is increased by lowering the center of gravity. Stability is also increased if the base is expanded by placing the feet farther apart.

Animals such as chickens have easier systems to control. Figure 9 shows that the cg of a chicken lies below its hip joints and between its widely separated and broad feet. Even relatively large displacements of the chicken's cg are stable and result in restoring forces and torques that return the cg to its equilibrium position with little effort on the chicken's part. Not all birds are like chickens, of course. Some birds, such as the flamingo, have balance systems that are almost as sophisticated as that of humans.

Figure 9 shows that the cg of a chicken is below the hip joints and lies above a broad base of support formed by widely-separated and large feet. Hence, the chicken is in very stable equilibrium, since a relatively large displacement is needed to render it unstable. The body of the chicken is supported from above by the hips and acts as a pendulum between the hips. Therefore, the chicken is stable for front-to-back displacements as well as for side-to-side displacements.

The center of gravity of a chicken is below the hip joints. The chicken is in stable equilibrium. The body of the chicken is supported from above by the hips and acts as a pendulum between them.



Engineers and architects strive to achieve extremely stable equilibriums for buildings and other systems that must withstand wind, earthquakes, and other forces that displace them from equilibrium. Although the examples in this section emphasize gravitational forces, the basic conditions for equilibrium are the same for all types of forces. The net external force must be zero, and the net torque must also be zero.

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