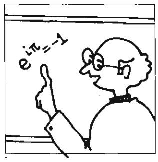
Classroom



In this section of* Resonance, *we invite readers to pose questions likely to be raised in a classroom situation. We may suggest strategies for dealing with them, or invite responses, or both. "Classroom" is equally a forum for raising broader issues and sharing personal experiences and viewpoints on matters related to teaching and learning science.

Which Way does the Flame Point?

Jaywant H Arakeri
Department of Mechanical Engineering
Indian Institute of Science
Bangalore 560 012, India.
Email:
jaywant@mecheng.iisc.ernet.in

Consider the following experiment: lighted candles are placed at each end of a rigid bar pivoted in the centre and rotating in a horizontal plane; the candles are enclosed in transparent containers (*Figure* 1). When the bar is not rotating the flames points upwards. Which way do the flames point when the bar is rotating?

To answer this question let us look at some related problems. Consider a body (heavier than air) hanging from the end of a rotating arm. We know from observation that the body will swing outwards, a fact that can be explained by centripetal acceleration. Body moving with constant speed V in a circular

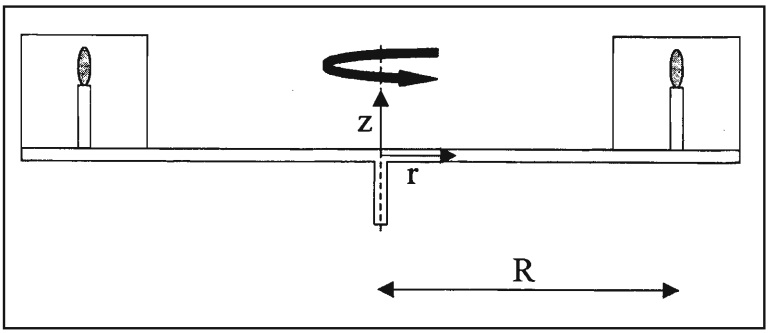
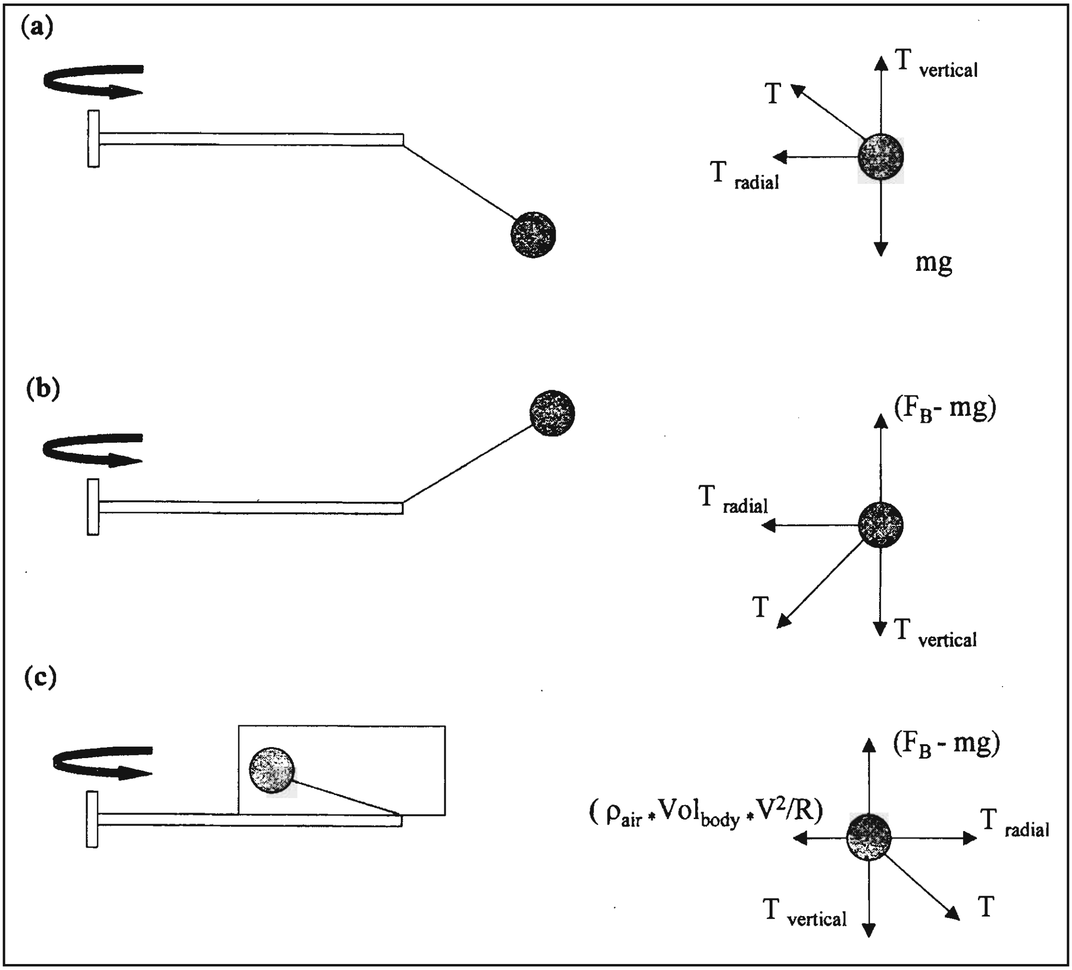


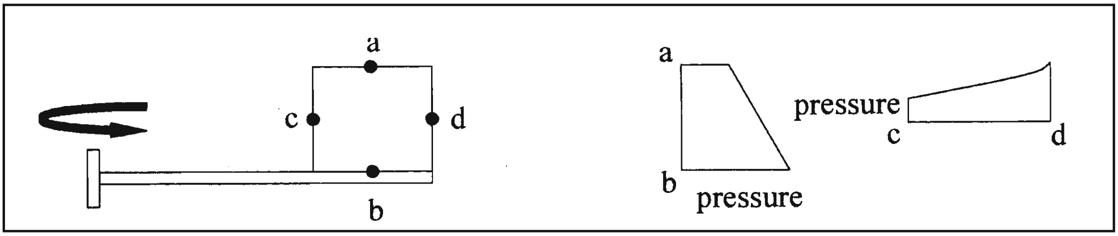
Figure 1. Figure showing the experimental setup. Two lighted candles are placed at the ends of a rotating bar.

path of radius R experiences an acceleration V^2/R – the centripetal acceleration – towards the centre of the circle. A force, the centripetal force, mV^2/R is required to provide this acceleration; m is mass of the body. The radial component of tension in the string provides this force. (*Figure* 2a). The vertical component of tension balances the weight of the body.

What happens if the body is lighter than air, say a small helium filled balloon? When the bar is stationary the body points upwards due to the buoyancy force. When the bar is rotating, as in the previous case, the body is flung outward with the radial component of the tension again providing the necessary centripetal force (*Figure* 2b)

Figure 2. (a) A body hung at the end of a rotating bar swings outward. Force balance gives $T_{radial} = mV^2/R$ and $T_{vertical} = mg$. (b) A body, lighter than the surrounding air, also swings outward. F_B is the buoyancy force. (c) If the lighter body is enclosed it swings inward.





$$T_{radial} = mV^2/R = \rho_{body}\,(\mathrm{Vol})_{body}\,V^2/R,$$

where ρ_{body} and $(\mathrm{Vol})_{body}$ are the density and volume of the body, respectively. The vertical component of the tension balances the weight of the body and the buoyancy force: $T_{vertical} = (\rho_{air} - \rho_{body})\,(\mathrm{Vol})_{body}\,g$. (Note in the above two cases the bodies will be also pushed 'back' due to the air drag.)

Figure 3. Weight of the air sets up a pressure field that increases linearly downwards, for example, from point a to point b. Circular motion of the enclosure sets up a pressure field in the air that increases radially, for example, from point c to point d. The radial pressure gradient provides the necessary centripetal force for the enclosed air.

However if an enclosure is placed around the lighter body something strange happens. Instead of the body being flung outward it is 'pushed' inward. To understand this we need to look at the air in the enclosure. The weight of the air causes the pressure to increase linearly downwards, $\partial P/\partial Z = -\rho_{air}\,g$ (*Figure* 3), where ρ_{air} is air density and Z is distance measured upwards. (The atmospheric pressure ($\sim$1kgf/cm^2) around us is due to the weight of the air in the atmosphere). In addition, the air in the enclosure moves around in a circular path with velocity V. So each fluid element needs a centripetal force which is provided by pressure in the air that increases with radius (*Figure* 3),

$$\frac{\partial P}{\partial r} \approx \frac{\rho_{air} V^2}{R},$$

where r is the radial distance[1]. Here we are assuming that the dimension of the enclosure is small compared to R. The force due to this pressure field on the body will be

$$\left(\frac{\rho_{air} V^2}{R}\right)(\mathrm{Vol})_{body}$$

[1] The pressure increasing with radius can be made visible by partially filling the enclosure with water: when the bar is rotating, the surface of the water tilts with outer level higher than the inner level.

This force will point towards the centre of rotation and will be

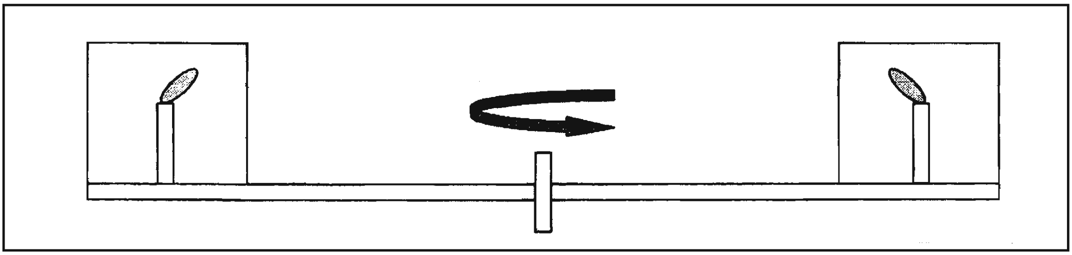


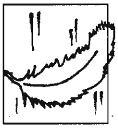
Figure 4. The radial pressure field in the air pushes the lighter flame inwards, just like the vertical pressure field (set up by the weight of the air) pushes the flame upward.

greater than the centripetal force $(\rho_{body}\, V^2/R)\,(\mathrm{Vol})_{body}$ that is required by the body. Thus the body tilts inward; the excess force due to the fluid pressure is balanced by the radial component of the string tension which now acts outward (*Figure* 2c).

$$T_{\mathrm{radial}} = \left(\rho_{\mathrm{air}} - \rho_{\mathrm{body}}\right)\frac{V^2}{R}\,(\mathrm{Vol})_{\mathrm{body}}$$

In other words Archimedes' principle in the radial direction causes the (lighter) body to tilt inwards!

Finally, we come to the candle problem. The flame in a stationary candle points upwards because the gases composing the flame are lighter than air. The flame in an enclosed candle on the rotating arm will be pushed inwards by the *rotating* heavier air in the enclosure in a similar way as the lighter body was pushed inwards in the above example. Which way will the flame point if the candle is not enclosed (assuming the flame does not get extinguished)?



A common sense interpretation of the facts suggests that a superintellect has monkeyed with physics, as well as with chemistry and biology, and that there are no blind forces worth speaking about in nature. The numbers one calculates from the facts seem to me so overwhelming as to put this conclusion almost beyond question.

Fred Hoyle