Another Look at the Wine Butler

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In a recent article, Iain MacInnes analyzed the static equilibrium of a system consisting of a wine bottle and a wine butler.[1] After discussing that composite system, students can be asked to consider only the bottle (and its contents) as the system. An interesting challenge for them is to describe the forces on the bottle in static equilibrium.

At first glance, it may appear that there are only two forces acting on the bottle as shown in Fig. 1: the downward gravitational force and an upward force exerted by the wine butler. If the two forces have equal magnitudes, they satisfy the condition that the net force bottle is zero. However, those two forces would result in a net clockwise torque with respect to any point, so something is wrong with this analysis.

A closer inspection reveals that the wine butler touches the neck of the bottle in two places: on the top closer to the lip and on the bottom closer to the shoulder. The correct free-body diagram with a downward force F_d near the top of the neck and an upward force F_u farther down the neck is shown in Fig. 2. If the distances between the forces are s and c as shown, the conditions for static equilibrium are

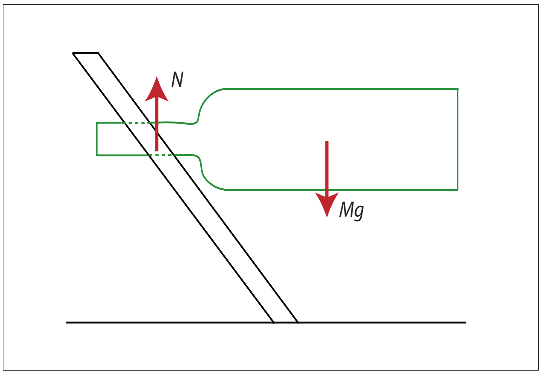

Fig. 1. An incorrect free-body diagram for the bottle.

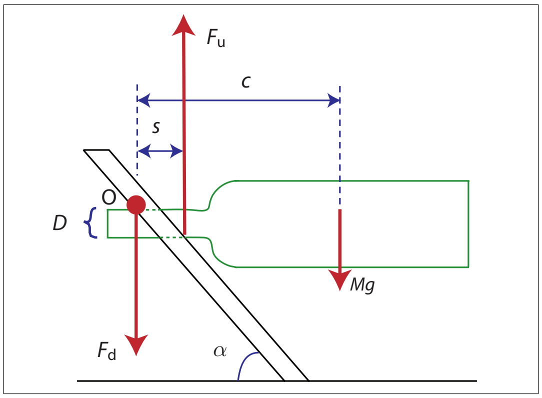

Fig. 2. The correct free-body diagram for the bottle.

no net force:
$$F_u = Mg + F_d,$$

no net torque:
$$F_u s = Mg\,c.$$

The torques in the second equation are calculated about the point (O) where the downward force acts. Both equations imply that the upward force must be larger than the weight of the bottle.

The relative size of the forces can be estimated using the data from Ref. 1:

$c = 12$ cm

and

$\alpha = 36^\circ$,

and the neck's diameter, which is $D = 2.5$ cm for a typical bottle. Ignoring the thickness of the wine butler, we have approximately:

$$s \approx D/\tan\alpha = 3.4 \text{ cm}.$$

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The upward force is predicted to be $c/s \approx 3.5$ times as large as the bottle's weight and the downward force about 2.5 times as large as the weight.

The predictions above were tested using a bottle with a weight of $Mg = 12$ N. Using a Dual-Range Force Sensor,[2] I measured the forces on the bottle while it was held in the orientation shown in Fig. 2. To determine the upward and downward forces, a metal beam was positioned to apply one of them while a loop of string attached to the sensor applied the other. The measured forces were $F_u = 40 \pm 2$ N and $F_d = 27 \pm 2$ N, where the uncertainties were due to the difficulty in placing the string exactly where the wine butler contacted the bottle. The ratios between the contact forces and the weight, $F_u/Mg = 3.3 \pm 0.2$ and $F_d/Mg = 2.3 \pm 0.2$, agree well with the predictions above.

Students who have difficulty picturing the two contact forces could experiment with holding a pencil or a pen horizontally near one end between horizontal index and middle fingers. If they don't squeeze their fingers together too hard, the offset between places where they apply forces should be obvious. Students can also confirm that bringing the fingers closer together (reducing s) requires squeezing harder (increasing F_u and F_d).

The wine bottle is similar to the match in a balancing spoon-fork-match system discussed in an earlier article.[3] The correct analysis of that problem requires the same care in identifying all of the forces.[4]

References

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3. Robert G. Kirkham, "Choosing the right system for analysis of forces," *Phys. Teach.* **34**, 402–403 (Oct. 1996).
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