Two Experimental Approaches of Looking at Buoyancy

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Two Experimental Approaches of Looking at Buoyancy

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In our teaching practice, we find that a large number of first-year university physics and chemistry students exhibit some difficulties with applying Newton's third law to fluids because they think fluids do not react to forces.

We recently carried out an investigation involving 98 students (58 physics, 40 chemistry). For all students, the existence of a buoyant force when a body is within a liquid, as well as its numeric calculus, is supposed to be well known since this is a required topic in secondary school. In our investigation, we used one of Paul Hewitt's "Figuring Physics" challenges,[1] as shown in Fig. 1, and asked students to choose which answer was correct.

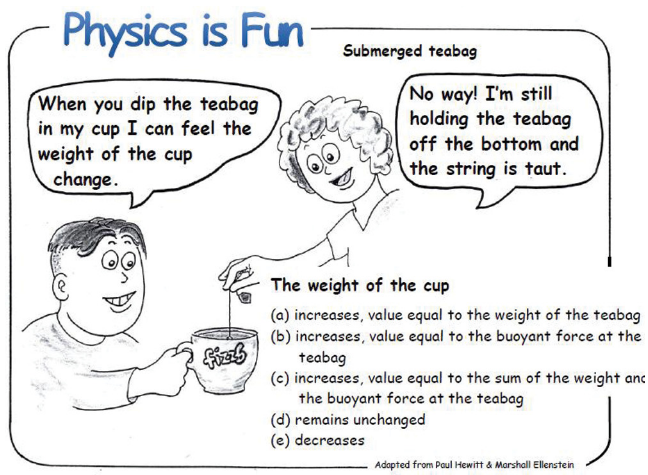

Fig. 1. Challenge concerning buoyant force.

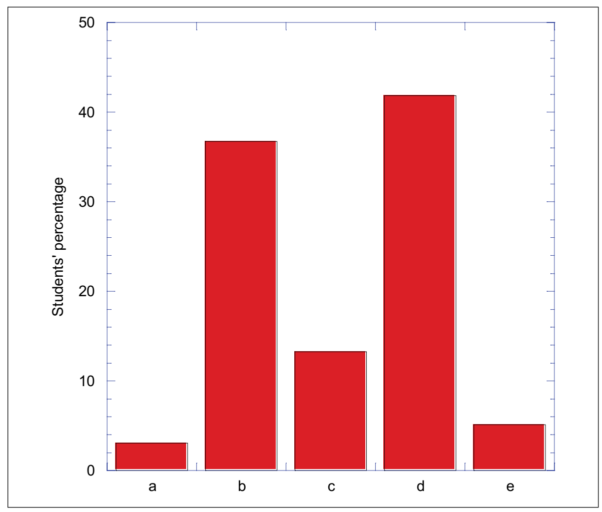

Fig. 2. Students' answers in percentage.

Figure 2 presents students' answers in a bar chart. The main conclusion is that the majority of students (63.3 %) gave a wrong answer, 41.8 % of them choosing answer (d) (nothing happens, see also Ref. 2). Amazing is the fact that 5.1% of students believe that the cup's weight decreases [answer (e)], which is indeed an influence from daily experience when we take a teabag from water and feel that it is heavier.

It is therefore important that we try to find adequate strategies that support a good understanding of this topic. Some years ago, Eric Kincanon[2] published a short paper with an interesting demonstration and explanation relating buoyancy and Newton's third law by using a balance and a beaker of water. The explanation was totally based on calculations, and no recorded data were presented. According to Randall Knight,[3] students get a better understanding when they undergo an experimental activity where they can measure physical quantities and then try to interpret the results by modeling data. With this in mind, we suggest a quantitative experiment whose explanation is based on both hydrostatics and Newton's third law.

The experiment is carried out by placing a beaker of water on a calibrated balance with a precision of 0.1 g. We first record the mass of the water. Then, a steel sphere of 38.05± 0.05-mm diameter is suspended by a wire from a spring scale having a precision of 3 g, which enables us to access its weight (this could also be done with a force sensor, if available, which usually has better resolution). Figure 3(a) depicts the experimental setup. Subsequently, the sphere is immersed completely into water, as is shown in Fig. 3(b), ensuring that it does not touch the bottom of the water container.

The new values indicated by both the balance and scale are again registered. Table I shows the values indicated on both instruments. Within experimental errors, we observe that the numeric variations obtained from both instruments are nearly symmetric.

In order to understand these results, let us consider, as the first approach, the system formed by the water, the beaker, and the sphere. The sphere's weight does not depend on its position in the water when it is immersed. Therefore, the total external force on the system, composed of the sum of the tension in the suspending wire and the normal reaction force from the balance plate, must remain constant.

We have ascertained that the tension in the wire that holds the sphere in equilibrium decreases by about (30 g)(g)≃ 2.9×10^4 dyn when the sphere is plunged into the water without touching the bottom of the container. Thus, in order to keep the total external force constant, the normal reaction force from the balance plate needs to increase by the same amount—Newton's third law. This feature can be understood and explained in the following way: whenever the sphere is immersed in the water, it experiences the buoyant force from the water. The change in the tension of the suspending wire

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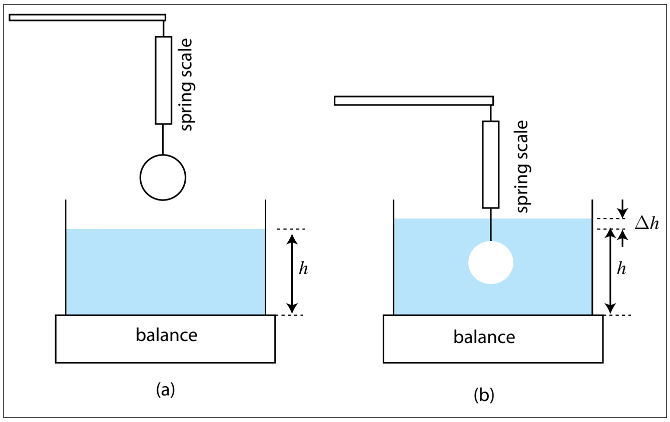

Fig. 3. Experimental setup.

is equal to this buoyant force. As a result of Newton's third law, the sphere exerts a downward vertical force on the water that will change the pressure at the points where the water contacts the sphere. Because of Pascal's law,[4] the change of the pressure will spread equally to every point through the liquid, in particular to those located at the bottom of the container. Thus, the force due to the container over the balance plate increases by the same amount of the buoyant force on the sphere, whose value is equal to about (30 g)(g).

An alternative interpretation of this feature (the second approach) stems from the fundamental law of hydrostatics. Let us first consider the water container without the sphere [Fig. 3(a)]. The pressure experienced at the points located at the bottom of the container can be evaluated from the equation:[4]

$$P = \rho g h + P_0.$$

On plunging the sphere into the water, whose volume is V, the level of the water in the container increases to $h + \Delta h$ [Fig. 3(b)]. Thus, the pressure at the bottom of the container is now given by the *hydrostatics fundamental law:*

$$P' = \rho g h + \rho g \Delta h + P_0 = P + \rho g \Delta h.$$

As the change of pressure is $\Delta P = \rho g \, \Delta h$, the corresponding change of the force due to the pressure at the bottom of the container is:

$$\Delta F_p = S \Delta P = \rho g (\Delta h S),$$

where S is the area at the bottom of the container. Since water can be considered as an incompressible fluid, the apparent increase of water volume $\Delta h S$ is equal to the sphere volume. Then

$$\Delta F_p = \rho g V_e.$$

Table I. Values measured when the sphere is in air and completely immersed in the water, as well as the corresponding shifts.

Instrument	In air	In water	Shift
Spring scale reading (g)	225 ± 3	195 ± 3	-30 ± 6
Balance reading (g)	2197.8 ± 0.1	2226.7 ± 0.1	29.9 ± 0.2

By using the measured value of the sphere diameter and the values of $\rho = 10^3$ kg/m^3 and $g = 9.8$ m/s^2, we obtain ΔF_p = 0.283 ± 0.001 N. This value is actually comparable with ΔF_b = 0.293 ± 0.001 N, obtained from the balance. Thus, we can conclude that the increase of the value measured at the balance corresponds to the change in the water pressure at the bottom of the container, due to the increase of the free surface level of the water.

This experiment and the two approaches provided in this work can be used as complementary explanations of the buoyancy concept relating Newtonian mechanics (Newton's third law) with fluid mechanics (Archimedes' and Pascal's laws), which gives a rich environment for students' understanding of physics.

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