Hands-on experiences with buoyant-less water

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Hands-on experiences with buoyant-less water

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Abstract
The phenomenon of weightlessness is known to students thanks to videos of amazing things astronauts do in spaceships orbiting the Earth. In this article we propose two hands-on activities which give students opportunities to infer by themselves the absence of buoyant force in a gravity accelerated system. The system is a free-falling or vertically tossed bottle filled with water with a small, inflated balloon attached to the bottom by a spring. Practical hints on how to make efficient demonstration experiments are added.

S Online supplementary data available from stacks.iop.org/physed/45/292/mmedia

According to Pais [1], in November of 1907 Einstein realized that a person falling freely would feel weightless. This idea, which was later fully developed, became the cornerstone of the general theory of relativity, known as the principle of equivalence: effects due to gravitational field and accelerated motion are equivalent.

Einstein did not live long enough to watch on YouTube those videos showing amazing phenomena due to the weightlessness in artificial satellites orbiting high above the Earth [2]. Nevertheless, on his 76th birthday (which turned out to be his last one), Einstein obtained from Eric Rogers a puzzling device [3]. He was delighted with this present and solved the puzzle at once, applying the consequence of the equivalence principle: weightlessness occurring in free-falling systems.

So, it seems that in 1955 Rogers designed the first 'pedagogical' demonstration of weightlessness near the ground. The device given to Einstein as a birthday present is shown in figure 1.

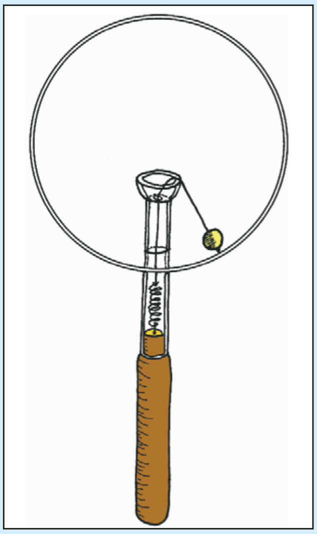

Figure 1. The birthday present given to Einstein.

The main part of the device is a solid-brass ball which is attached to a spring. As can be seen, the spring is not strong enough to pull the ball up into the cup. The puzzle was to imagine a sure method to bring the ball into the cup, without opening the transparent globe. Einstein lifted the device, left it to fall freely and the ball ended up in the cup.

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Over the years, physics educators have proposed simpler versions of ‘Einstein’s toy’ [4] and found other pedagogical demonstrations of weightlessness [5]. For instance, if water happens to be in a free-falling bottle, it would be weightless and would behave in a way which challenges ordinary experience: it would not flow out through a hole in the bottle [5–7]. In addition, the water, due to its weightlessness, would be unable to exert a buoyant force.

Buoyant-less water in physics textbooks

These counterintuitive consequences of water’s inability to exert a buoyant force in some particular situations are very rarely used in physics textbooks as vehicles for deepening students’ comprehension of buoyancy. One example is the following:

> ‘A block of wood floats half submerged in a container of water. If the same container were in an Earth-orbiting satellite, how would the block float? Explain your reasoning.’ [8]

A more common approach is just to ask about the very existence of the buoyant force in orbiting systems:

> ‘Does Archimedes’ principle hold in a satellite orbiting the Earth in a circular orbit? Explain.’ [9]

> ‘Is Archimedes’ principle applicable in a spacecraft orbiting the Earth? Explain carefully.’ [10]

> ‘Suppose that an orbiting space station of the future had a swimming pool in it. If there is no artificial gravity, would a buoyant force be exerted on a swimmer? Explain.’ [11]

What these examples share is that students have to accept conceptually this ‘strange’ phenomenon without being able to experience personally its visible manifestations due to the simple fact that it happens ‘only’ in satellites.

We know just one textbook author who suggested that this phenomenon might happen on the Earth:

> ‘A ping-pong ball is attached to the bottom of a pail by a rubber band. The pail is then filled with water until the ball is at rest below the surface of the water . . .. The pail, with water, ball, and rubber band, is then carried to the top of a tall building and released from rest at the edge of the roof. The motion of the ball relative to the pail is then best described as follows:
>
> (a) The ball moves initially toward the bottom of the pail.
> (b) The ball initially moves toward the surface of the water.
> (c) The ball remains at rest below the surface of the water.
> (d) None of the above correctly describes the motion of the ball during the fall off the roof.’ [12]

Although it is a step in the right direction, a comment is necessary. Namely, the suggestion that the pail should be ‘carried to the top of a tall building’ might mislead students to conclude that the disappearance of the buoyant force is an effect having something to do with the great height and that it cannot happen in room size dimensions.

Reports on experimental demonstrations of this phenomenon are rare [13]. We found only two articles, both written by the same author, that explicitly address the demonstration of the absence of buoyancy in free fall [14, 15]. Note that in [13] buoyancy (in combination with a drag force) is employed only to slow down the motion of the object before the system is set to free fall.

In this article we propose two hands-on activities which will give students nice opportunities to infer by themselves the absence of buoyant force in water when it forms part of a gravity accelerated system. In our case, the system is not a satellite but a free-falling or vertically tossed bottle filled with water. The absence of the buoyant force can be inferred from the behaviour of a small, inflated balloon, attached to the bottle by a spring. Although a similar idea is used in [14], our design allows better visibility of the phenomenon for the whole class. We also add practical hints on how to make an efficient demonstration experiment as well as extension to a second activity. The design of a demonstration experiment can also be given as a project task for students.

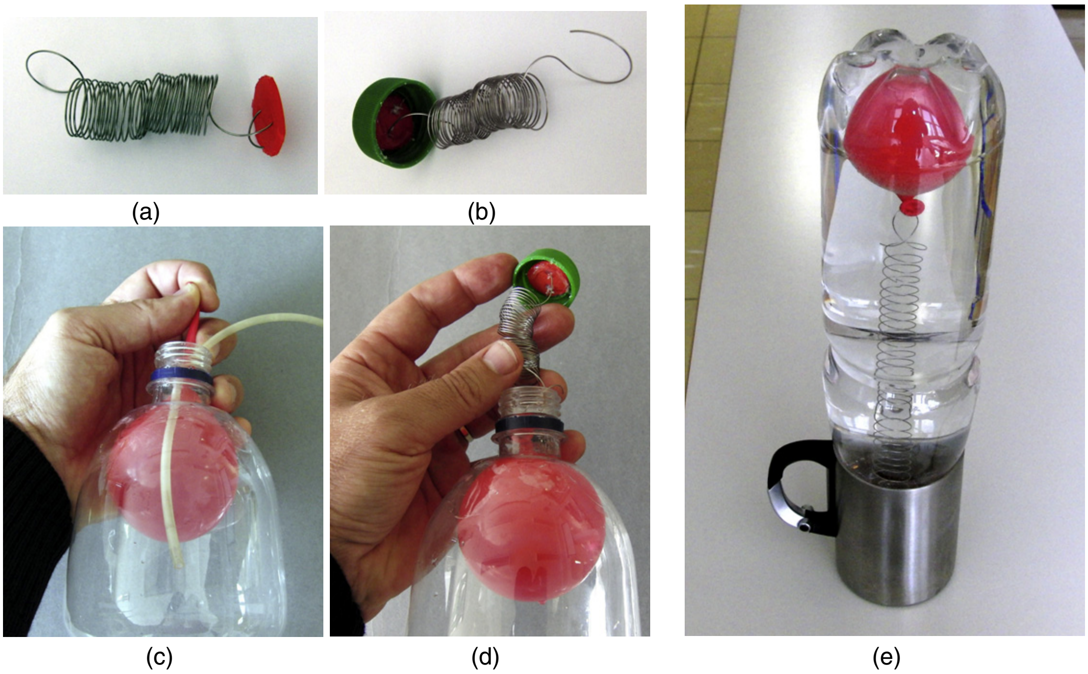

Figure 2. Assembling the demonstration experiment.

Experiments

You will need a large soda bottle (for the best performance, use a 2 l bottle with as few corrugations as possible), a button or other piece of flat plastic, a soft spring, a thin hose and small balloons, known as water balloons. You will also need a glue gun (hot plastic pistol).

Hook one side of the spring to the button (figure 2(a)) and glue the button into the bottle cap using the glue gun (figure 2(b)). Place the balloon in the bottle neck, leaving the open end of the balloon outside the bottle. If you try at this point to blow the balloon up, you will realize that this cannot be done, no matter how hard you blow. You can challenge your students to explain why it is so and what one can do in order to be able to blow the balloon up inside the bottle. The solution is to use a thin hose, which ensures that the pressure in the bottle remains equal to the ambient pressure during the inflation of the balloon (figure 2(c)). Do not inflate the balloon too much. A larger balloon is more visible, but it also experiences a larger drag force during the motion in water, and therefore has a longer reaction time. Once the balloon is inflated, tie it up and then tie it again on the end of the spring (figure 2(d)). Finally, fill the bottle with water, screw on the cap and turn the bottle upside down (figure 2(e)). Your buoyant-less water setup is ready for experiments.

Step on a chair and let the bottle fall into a box with Styrofoam chips. Repeat the experiment several times. The students will be able to see that soon after you release the bottle, the balloon moves towards the middle of the bottle (figure 3). In a stationary bottle, the buoyant force on the balloon is larger than the force of the spring. In a gravity accelerated bottle, the buoyant force vanishes but the spring force remains unchanged, and therefore pulls the balloon down.

In the second experiment, toss the bottle vertically upwards and catch it when it falls down. Again, repeat the experiment several times. The students will be able to see that soon after the bottle leaves your hands, the balloon moves towards the middle of the bottle (figure 4). In a stationary bottle, the buoyant force on the balloon is larger than the force of the spring. A bottle that freely moves vertically upwards is also gravity accelerated and therefore in this case the buoyant force vanishes as well. Initially, the outcome of this experiment may be less surprising for the students than the outcome of the previous experiment.

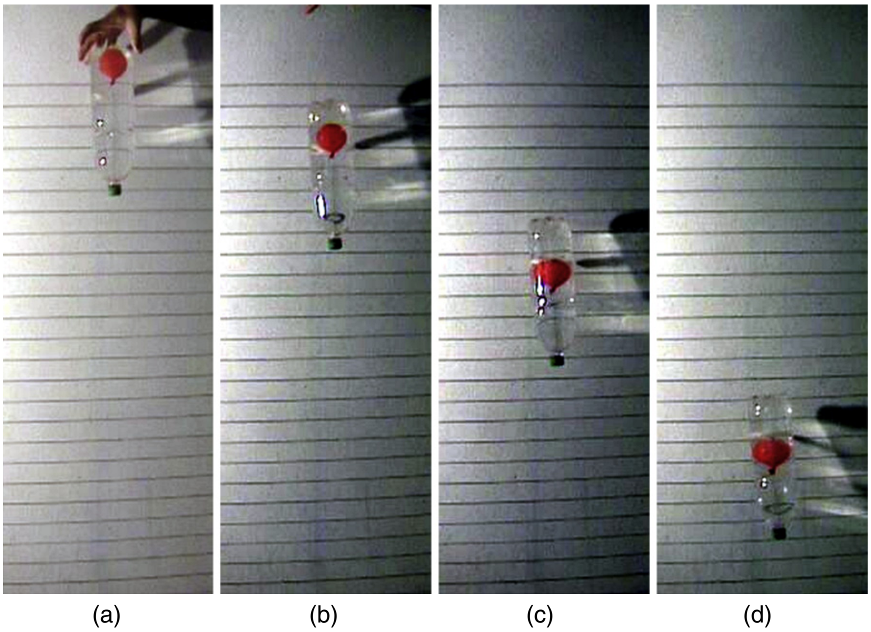

Figure 3. Bottle in free fall; (a) when released ($t = 0$), (b) at $t = 125$ ms, (c) $t = 250$ ms and (d) $t = 375$ ms.

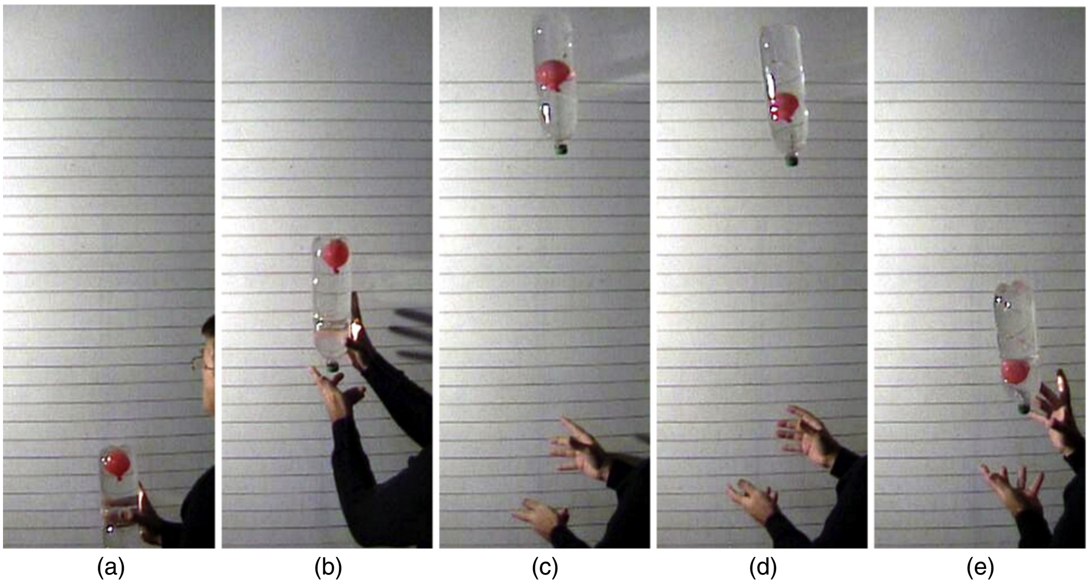

Figure 4. Bottle tossed vertically; (a) stationary, before tossing, (b) after leaving hands ($t = 0$), (c) at $t = 250$ ms (moving upwards, just before reaching the highest point), (d) $t = 500$ ms (moving downwards) and (e) 750 ms (moving downwards).

Seeing the initial upward acceleration of the bottle, their reasoning is an analogical elaboration of a kinaesthetic experience. ‘When a person is in an elevator that is moving up from rest, she or he feels heavier. Consequently, when ‘heavier’, the balloon should move down’. However, analysis of the video recording reveals that the balloon did not move down at all during the upward acceleration of the bottle (figures 4(a) and (b)).

In fact, the buoyant force during this period is even larger than in the stationary case. The balloon only began to move down during the decelerated motion of the bottle (i.e. after the bottle left the teacher's hands, figures 4(c)–(e)), which is again consistent with the explanation given above.

The results of the two experiments can also be seen in short movies at stacks.iop.org/physed/45/292/mmedia.

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