Fizziology

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Abstract
Most students consume fizzy drinks and will have seen the bubbles that appear when the drinks are poured. But how much gas is in the bottle or can? Simple investigations can answer this and other questions both theoretically and experimentally.

Gases can be dissolved in liquids. The higher the pressure of gas above a liquid, the more gas molecules will be found in it. Fizzy drinks contain dissolved carbon dioxide. In order to keep the gas in the liquid the fizzy drinks are under pressure (typically about 2 bars, i.e. twice atmospheric pressure) before we open the container. When the bottle or the can is opened, gas starts to leave the liquid. This goes on until a new balance at atmospheric pressure is reached, or in other words until the drink is flat. If this were the whole story we would expect bubbles to form everywhere throughout the liquid. But if you carefully observe a glass filled with fizzy drink you will notice that the bubbles form mainly on the walls of the glass. Most often they form on small particles such as motes of cellulose left over from drying that contain tiny pockets of air. This suggests that the energy required to form the bubble somewhere inside the liquid is too large for the conditions typically met in fizzy drinks. But it also shows that the energy required for the dissolved gas molecules to penetrate the trapped air pockets is sufficiently low for this to happen. Therefore the trapped air pockets are where the bubbles start to form. Each bubble grows and grows until it reaches a critical size and then it breaks away from the wall. On its way to the surface the bubble grows further, not so much because of the decrease in hydrostatic pressure but more because dissolved gas is constantly penetrating it.

There are several excellent articles that describe the evolution and the dynamics of the air bubbles in fizzy drinks [1–3]. We will present here some simple experiments that can help teachers to demonstrate some basic physics related to fizzy drinks and can be used to motivate students to do some quantitative analysis using fizzy drinks.

How much carbon dioxide is dissolved in a fizzy drink?

We all know that if the fizzy drink is left opened it will eventually go flat. Here is an intriguing question: what is the volume of carbon dioxide dissolved in the drink compared with the volume of the drink under normal conditions? Many students will say that the volume of the gas must be much smaller than the volume of the liquid from which this gas comes.

Let us first see what information we can find on the label of the bottle or can. On most soft drinks containers it is written that there is at least 4.9 g of CO_2 dissolved in each litre of the drink. Using the periodic table of the elements we may find that each mole of CO_2 has a mass of 44 g. The ideal gas law tells us that each mole of the gas occupies a volume of about 25 litres at normal pressure and room temperature. The estimated volume of the dissolved CO_2 in 0.5 litre of fizzy drink is therefore

$$V_{CO_2} = \frac{4.9\ \mathrm{g\,l^{-1}} \times 0.5\ \mathrm{l}}{44\ \mathrm{g\,mol^{-1}}} \times 25\ \mathrm{l\,mol^{-1}} \simeq 1.4\ \mathrm{l}$$

i.e. almost three times larger than the volume of the drink itself! Is that correct? Some clever students

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Figure 1. The CO_2 from the bottle on the right will replace all the water in the bottle on the left in a few hours.

may comment that not all the gas can leave the drink because we live at a pressure of 1 bar. Very good! The initial pressure in the bottle was about 2 bars, so the corrected estimation for the volume of the released CO_2 from the 0.5 l bottle is about 0.7 litre (those who need a more rigorous derivation should look for Henry's law). But the conclusion did not change: the volume of gas that is dissolved in the fizzy drink is larger than the volume of the drink itself—under normal conditions. For many students this result is surprising and therefore it calls for experimental verification.

The idea is simple: let's trap all the gas that leaves the fizzy drink and measure its volume at normal pressure. But the problem is that the gas is invisible. Chemists solved this problem long ago: let the gas displace some liquid and then we measure the volume of the liquid that has been displaced. The experiment should be designed so that the pressure of the gas is close to atmospheric pressure. The experiment can be done with common materials that one can find at home (see figure 1). All you need is a bottled fizzy drink, an empty bottle with a plastic cap, a spare plastic cap, two straws with flexible knees and some material to seal the straws into the caps (I used five-minute epoxy). Prepare the caps and straws as shown in the figure before you open the bottle of fizzy drink. Make sure that the holes in the caps are of the same diameter as the straws. It is very important that any gaps between the straws and caps are sealed completely. Then fill the empty bottle with water, cover it with a cap and place it in a tilted position as shown (this position also minimizes the effect of hydrostatic pressure in the bottle filled with water). I have filled the 'Quality Street' tin with rice in order to prevent the bottle of water from rolling. Now open the bottle of fizzy drink and quickly screw on the cap at the end of the straw by turning the bottle. Wait until you see the water in the lower straw start to rise. This may take more than five minutes. Then leave the experiment and check it every hour. In about three to four hours the gas from the half litre of fizzy drink should replace half a litre of water.

How to demonstrate in front of the whole class that the bubbles are more likely to form on the tiny motes?

Take a plastic Petri dish (or any transparent plastic cover such as found on some spreads or yoghurts) and rub parts of it with a fine sandpaper (not the whole dish!). Cut a circular hole the size of a Petri dish in a cardboard mask. Put the mask on the overhead projector and put the Petri dish on it. Now pour the fizzy drink into the Petri dish, just enough to cover the bottom, and watch.

The picture on the screen reveals that the bubbles are more likely to grow just where the plastic was scratched with the sandpaper (figure 2). The speed of bubble growth depends on the type of beverage. Sweet drinks have in general a lower surface tension, which makes the bubbles less stiff and more mobile in a shallow Petri dish than bubbles from carbonated mineral water.

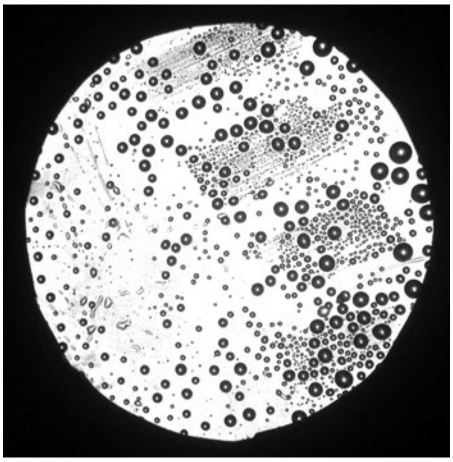
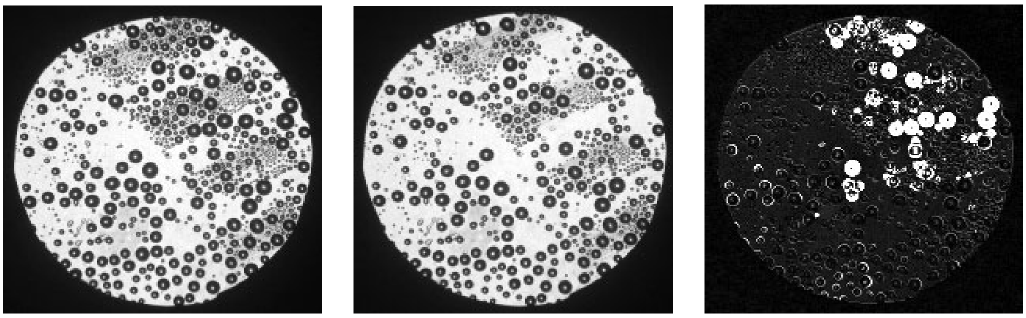


Figure 2. Formation of bubbles from the carbonated mineral water at cracks (four stripes). The picture was projected with an overhead projector (original size 1.5 m × 1.5 m).



(*a*) (*b*) (*c*)

Figure 3. Image of the bubbles from the carbonated mineral water in a Petri dish: (*a*) initial, (*b*) after a few minutes, (*c*) difference.

How big can the air bubbles grow before they leave their birthplaces?

As explained above, bubbles grow from tiny motes or cracks but at some point they break away from their birthplaces and rush toward the surface of the liquid. This happens at the moment when the buoyancy of the bubble exceeds the surface tension forces keeping the bubble attached to the wall. The limiting size of the bubble therefore depends mainly on the type of dissolved gas, the density of the liquid, and the forces between the molecules of the liquid and the molecules of the solid walls. All these parameters are fixed for a given beverage and given container, so we can expect in any particular case that the bubbles will separate from the walls when they reach a certain critical size. How can one determine the average critical diameter of the bubbles in the Petri dish?

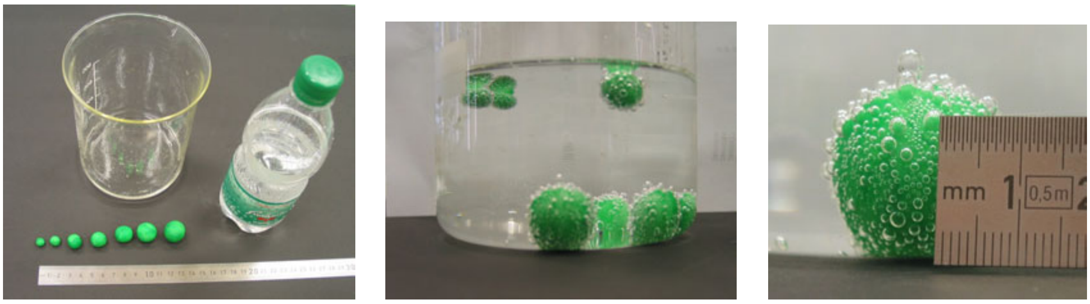
It is hard to make systematic observations of the crowd of bubbles in the Petri dish with the naked eye. The following procedure makes the observation easier.

Fix your digital camera on a tripod or place it on a table and take a photo of the projected image of the bubbling beverage on the screen. Don't move the camera! Take another photo from exactly the same position a few minutes later (use a remote controller to operate the camera, if you have one). Transfer the images to your computer and subtract one from the other (in my Corel PhotoPaint I go to *Image, Calculations...* and choose *difference* method). You can also change the images to black and white to save the memory. A new image is generated which shows the differences between the two original images in a bright colour (white in our case), and therefore shows only those bubbles that have disappeared (figure 3). It is now easy to count how many bubbles have disappeared and determine the average critical diameter of the bubble. In our case (carbonated mineral water and plastic Petri dish) we obtained an average critical diameter of 3.8 mm. Note that the depth of the liquid in the Petri dish was only slightly greater than the size of the critical bubbles, so the largest bubbles were flattened, making their diameter appear larger than it would if they were spherical.

Any object immersed in the fizzy drink will soon be covered with small bubbles. The bubbles will grow and the buoyancy of the bubbles may eventually lift the object from the bottom to the surface—if the object is not too heavy. Once the object touches the surface, some bubbles are released and the object sinks again. This performance may repeat over and over. The effect is often demonstrated by putting some raisins into a fizzy drink but it also works with mothballs or plasticine balls. The latter are suitable for the following experiment, which can be extended in a project lab.

Make plasticine balls of different sizes as shown in figure 4(*a*). Determine the average diameter of each ball and measure their masses. Drop the balls into a glass container filled with a freshly opened fizzy drink and observe what happens. Watch for at least ten minutes. Carefully record your observations.

You will notice that all balls smaller than a certain size perform a dancing motion while larger balls never rise from the bottom. We will follow the simple explanation of this experiment that has been described elsewhere [4]. It may be assumed that the bubbles attached to the immersed



(*a*) (*b*) (*c*)

Figure 4. Plasticine balls smaller than a certain size rise (and sink) in the carbonated mineral water: (*a*) materials, (*b*) floating balls, (*c*) bubbles on the plasticine.

Table 1. Measured values obtained with typical school equipment.

Ball mass (g) ±0.02 g	Ball volume (cm^3)	Ball diameter (mm) ±0.6 mm	Ball floats?
0.28	0.2	7	yes
0.46	0.3	9	yes
1.45	1.1	13	yes
1.83	1.4	14	yes
2.67	2.0	16	no
3.88	2.9	18	no
5.24	4.0	20	no

object work as a 'bubble blanket' of thickness d that surrounds the object. As we know, bubbles grow but after some time they reach a critical size when they break away from the object. The critical size of the bubbles corresponds to the critical thickness of the bubble blanket. As the mass of the sphere is proportional to r^3 but the surface of the sphere increases only as r^2, there exists a ball of a maximum size that can just be lifted from the bottom by the attached bubbles. This limiting size of the ball can be easily determined from experiments with spheres of different sizes (see table 1). On the other hand, the simple theoretical model explained in [4] gives the following expression for the critical thickness of the bubble blanket:

$$d_c = r_{max}\left(\sqrt[3]{\frac{\rho_{ball}}{\rho_{liquid}}} - 1\right).$$

The measured values obtained with typical school equipment are summarized in table 1.

An average density of plasticine of 1.32 ± 0.1 g cm^{-3} can be determined by measuring the mass and the volume of a large piece of plasticine. I kneaded all the small balls into a large piece and used Archimedes' method (I have measured the amount of displaced water) to determine its volume. Knowing the masses and density of the balls, one can calculate their effective diameters assuming spherical shapes. Alternatively, direct measurements of the balls' diameters can be made, but the softness of the material and deviations from a spherical shape of the handmade balls require some measuring skills to obtain the same results. Assuming the density of the mineral water to be 1 g cm^{-3} and the diameter of the ball that barely floats to be 15 mm (mean value between the fourth and fifth balls in the table), one obtains $d_c = 0.73$ mm, which is in good agreement with the observed value (note that the bubble diameters range from less than 0.3 mm to about 2 mm and also that the surface of the ball is not completely covered with bubbles).

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Gorazd Planinšič received his PhD in physics from the University of Ljubljana, Slovenia. Since 2000 has led the undergraduate Pedagogical Physics course and postgraduate course on Educational Physics at the University. He is co-founder and collaborator of the Slovenian hands-on science centre 'The House of Experiments' and has also been secretary of GIREP since 2002.