

THEORY AND EXPERIMENT: ICE IN OIL

STUDENTS EXPLORE WHAT HAPPENS WHEN OIL IS POURED OVER WATER

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SUITABLE FOR AGE(S)

12 - 18 years

SUBJECT(S)

Physics, Chemistry

KEY FOCUSMaking predictions
Designing investigations**INTRODUCTION**

This task was inspired by a common introductory physics exercise and by a theoretical consideration presented during a workshop at the GIREP Conference in Jyväskylä in 2011. The primary goal is to explore buoyancy and density through both theoretical calculation and hands-on experimentation. Surprisingly, the experiment disproved theoretical predictions, providing an excellent platform for open inquiry.

The focus of this task is on the theoretical considerations involved in calculating the position of an ice cube in a liquid column, an experiment that tests the theoretical prediction, and an inquiry into why the two are not similar. Therefore, the aim of this task is to introduce students to both aspects: theoretical prediction and experimental testing.

The task emphasises upholding the idea that “an experiment is always right.” Theoretical predictions, which serve as the starting point, may not always match experimental results. These predictions can be incorrect or miss certain factors. To fully understand the experiment, it is often necessary to revisit the entire setup, ask multiple questions, and explore different phenomena that might or might not influence the outcome. If, after this process, a plausible explanation consistent with the experimental results is found, it is likely to be correct. Therefore, this activity primarily aims to develop skills in experimentation, questioning, and drawing conclusions.

For the task to be effective, students should initially understand the concepts of density and buoyancy. They need to be familiar with the definition of density and how density is calculated from measured quantities. They should also understand the expression used to calculate an object's buoyancy. From a mathematical perspective, students must be able to manipulate simple algebraic expressions and comprehend the meaning of the results they obtain.

TASK DESCRIPTION

This task transitions from theoretical prediction to experimental verification, aiming to bridge the gap between expectations and reality. Unexpected experimental outcomes prompt a deeper investigation into the physical phenomena involved, including density, buoyancy, surface tension, and hydrophobic interactions.

The question is simple, so is the experiment.

An ice cube is floating in a glass of water. What happens with the ice cube if the oil with a density lower than the density of ice is poured into the glass?

Two main theoretical predictions are considered:

- The ice will sink deeper into the water due to the additional pressure from the oil.
- The ice will float higher or even into the oil, as both water and oil contribute to buoyancy.

A simple experiment shows that the behaviour of the ice cube is far from predicted. The analysis of behaviour shows that it is not straightforward to establish conditions in which the simple calculated prediction holds. However, during the process, one can easily develop the activity into a serious and interesting open inquiry that connects physics, mathematics, and chemistry.

The introductory section of the task includes exercises in mathematics and physics. The middle section involves structured inquiry-based learning, while the final section features guided inquiry-based learning.

TASK PREPARATION

Since the task does not require specialised equipment, working in pairs is encouraged. However, for formulating tentative explanations, groups should be expanded to four members. The experiments can be conducted simultaneously within the same group; for example, one part of the group tests different cubes with varying densities, while another uses water with different amounts of dish soap. Be careful, as only heavily diluted dish soap should be used.

Materials needed:

For Each Group:

- Transparent glass (preferably one dL capacity, biodegradable if possible)
- Cold water (half-filled in a glass)
- Ice cube (preferably colored for visibility)
- Paper towels
- Kitchen oil (e.g., sunflower oil)- approx. one litre
- Stick, spatula, or knitting needle

Optional:

- Beaker with volume markings
- Kitchen scale
- Dish soap
- Funnel and filter for volume measurements
- Digital thermometer (for further inquiry)
- Ice cubes made from water with dissolved sugar (various concentrations)

TASK IMPLEMENTATION

Part 1: Theoretical Prediction

The cube of ice with density 917 kg/m^3 is put in the glass of cold water. Calculate the share of the cube's volume that is above the water. Draw the corresponding sketch that shows the proportions of ice above and below the water approximately.

Approximately $\frac{1}{11}$ th of the volume of ice is above the water. All the rest is below. The solution is given in the Appendix.

Now, the question is: What happens with ice if we pour a few cm of oil, which has a lower density than ice, into the glass? Let us assume that the density of oil is 850 kg/m^3 .

There are two possible predictions: either the ice will submerge below the water level, or the ice will float into the oil. There are also theoretically evidently wrong answers like ice remains where it is, or ice will sink to the bottom, or ice will float on the oil. However, let us focus the students' attention on the first two answers and ask them to explain the reasoning behind their prediction.

The reason why the ice should sink deeper to the water is that oil adds pressure and pushes the ice down.

The reason why the ice should move to the oil is that the oil also contributes to buoyancy.

The students are now asked to calculate the position of the ice in oil. Two calculation methods are presented in the Appendix. Both yield the same result as they are the two faces of the same phenomenon.

The ice should move significantly toward the oil. A significant part of the ice should be in the oil and only the minor part should remain in the water. The reason is simple: the density of oil is significantly larger than that of air; it is comparable to the density of water, and buoyancy contributes to both the displaced oil and the displaced water.

Part 2: Experiment

Now, let us verify. Students are organised in pairs. Experimental equipment is not a limitation, but it is always helpful to have a peer to discuss with. To promote social contact among students who are not close friends, it is recommended to draw memory cards for random pairing during this activity.

First part of the experiment in Part 1: Ice in water



The ice floats, a very small part of the ice cube is in the air (Figure 1).

To enhance visibility, the ice cubes were frozen water coloured by food colours.

Figure 1. Ice in water

Second part of the experiment in Part 1: Ice in water and oil

Students pour the oil to the glass half filled with water, in which the ice cube is floating. Add so much oil that the surface of the oil is a few centimetres above the surface of water. The height of the oil column should be at least 1 cm higher than the side of the ice cube.

Students observe what happens with the ice cube. They can push the ice cube down to the water with a spatula or a stick, they can mix the content, in principle, they can try whatever they like but they have to take care not to get oil on clothes or on other objects.

Results are unexpected. There could be several surprising observations, but very rarely does the ice cube move to the oil to the position predicted by calculation. In some circumstances, the ice cube moves slightly upward, but not as much as expected from the calculation (Figure 2, Left). In other circumstances, the ice cube floats in the oil (Figure 2, Right).

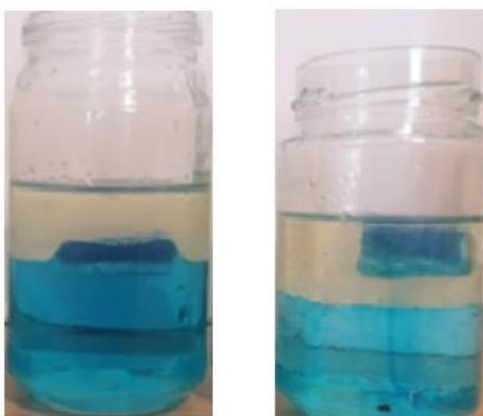


Figure 2. (Left) Ice floats in water but not much in oil. (Right) Ice floats in oil.

If it floats in the oil, another interesting phenomenon can be observed. The ice cube melts, the water from the melted ice collects at the bottom of the ice cube. At a certain moment the ice cube with the water drowns to the water below the oil, the water drop establishes a bridge to the water and flows to the water in the lower part. The ice cube, released of its water burden, moves up again to the surface of oil, where the process repeats (Figure 3).

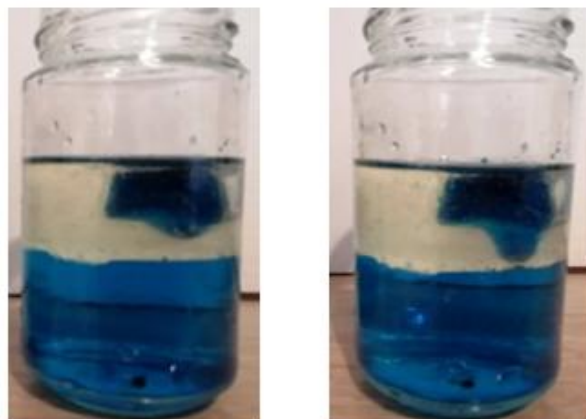


Figure 3. (Left) The drop of water starts to form. (Right) The drop of water pulls down the ice cube.

Open inquiry:

Students inquire about their own situation and their own ideas.

What could be a reason that the ice floats on the oil?

It is evident that the density of ice is smaller than the density of oil. But, how much? Is the data on the web or in books incorrect? So, one has to measure the density of both, oil and ice, to be sure about conclusions from the theoretical part. The lesson, when experimenting, one should not believe web or textbook data, as the materials used can differ.

How to measure the density of oil?

How to measure the density of ice?

It is therefore necessary to design experiments that allow us to calculate density. The procedure for measuring the density of oil is standard. The beaker is placed on the kitchen scale, and the scale is set to zero to measure the mass of the oil directly. Next, we pour a specified volume of oil. Therefore, we need the beaker with the scale for measuring volume. We then read the mass and calculate the density.

Measuring the density of ice is not so straightforward. One method is to place a beaker on the kitchen scale and set it to zero. Add several ice cubes prepared in the same manner to the beaker, then read and note the mass. Next, add cold water to the beaker and push the ice down so it is fully covered with water. Read the volume. Remove the ice cubes and measure the volume of the remaining water, or pour the water along with the ice cubes through a filter or a funnel with a smaller tube than the size of the ice cubes, and measure the volume of the water. From the difference between both volumes, the volume of the ice can be found, and its density calculated.

Because the purpose of the activity is to observe what happens to the ice in water when oil with a lower density than ice is poured onto it, the experimental conditions need to be established. Therefore, the next step is to find a way to modify the densities.

How to change the density of oil?

One can use a different oil, but usually it is not easy to find the oil on the spot. Nevertheless, one can also increase the density of ice.

How to change the density of ice?

There are several ways to alter the density of ice. Usually, the ice is frozen from regular tap water that contains dissolved gases. Boiling the water before freezing can sometimes increase its density sufficiently. No measurements are necessary; simply check if the ice cube floats or sinks in oil. If the density of the ice is still not high enough, adding sugar to the water can help. It is advisable for the "boiled" and "sweet" ice to already be prepared for students, who might have such ideas. When ice sinks in oil, some water is added to the glass, and the glass is left for a minute or two until the oil bubbles burst and the interface between the oil and water becomes straight.

Where is the ice cube positioned? Is it at the position predicted theoretically? What else can be observed?

The ice cube now floats at the water-oil interface, with a significant portion submerged in water. The part of the ice cube in oil is coated with a film of water. This situation involves a phenomenon that has not yet been addressed. Oil molecules are hydrophobic, meaning they strongly dislike contact with water. Consequently, the contact surfaces between water and oil tend to be as small as possible. The combined surface energy and potential energy of the ice cube, water, and oil should all be minimised.

A minimum energy condition is a useful, yet advanced, concept of free energy, commonly used in thermodynamics, but it is also highly applicable in mechanical contexts involving energy. For example, bubbles are spherical because this shape minimises the surface area in contact with air. A weight on a spring will settle where the combined elastic energy of the spring and the potential energy of the weight are minimised. The water in a glass forms a curved surface near the contact point with the glass because water molecules 'prefer' contact with the glass and 'pay' some potential energy to extend the number of molecules in contact. There are many similar examples in everyday life.

How is the water oil interface minimised?

Instead of ice being high up in the oil with a large contact area, it is now found lower with a bigger part in water. The interface area is smaller, but the potential energy of the displaced water is greater. To establish a new balance, another force opposing buoyancy must act — the surface tension at the oil-water contact.

How to test the idea that one has to consider surface tension in this system as well?

Let us eliminate surface tension. Repeat the experiment using water with a drop of dish soap, or simply add a drop of dish soap to the glass. The dish soap is denser than oil and sinks through the water, where it dissolves. You need to wait a little while, or

stir the water gently. The ice cube rises and is almost entirely in the oil, with only the lowest part in contact with water or slightly immersed in it (Figure 4).



Figure 4. One must increase the density of the ice and add dish soap to the water to reduce surface tension. All these are necessary to come close to the theoretical result of the calculation of a usual physics exercise

KEY LEARNINGS

The task was tested with in-service teachers in the online professional learning communities of teachers. As the equipment is simple, this task is suitable for remote experimentation or experimental homework after the position calculation has been completed in school.

CONCLUSION

Students often trust theoretical predictions more than their own eyes. In the classroom, it's common to see that students do not believe experimental results because these clash with their understanding or their interpretation of the "official" explanation. Sadly, this is sometimes true even for scientists.

This task demonstrates that whenever possible, one should compare the experiment with the theory. If they do not match, it is better to trust the experiment and seek possible reasons for the discrepancies. This activity specifically targets this conflict. If the experiment and the theory do not align, either the theory is wrong or not all relevant factors have been considered.

REFERENCES

S Faletič, M Gojkošek and K Jeličić, MUSE workshop: reflections and feedback, in Proceedings GIREP-EPEC Conference 2011: Physics alive, p. 191.

This reference discusses the outcomes of the workshop, where the initial theoretical problem of an ice-cube in water was examined theoretically. When we conducted the experiment afterwards at home, we realised that the theoretical consideration was too incomplete to explain the phenomenon, and we developed it into a serious inquiry.

APPENDIX

The context and additional information

Let us start with initial calculations.

The ice floats at the water surface, almost completely submerged to the water. The buoyant force and the weight are equal as it does not move.

$$\rho_{ice} V_{ice} g = \rho_{water} V_{displaced\ water} g \quad (1)$$

Here ρ marks density, V marks volume and g is gravitational acceleration.

If one says that a cube has a side of the size a , then it is easily shown that the ratio between the submerged volume of the cube and the whole volume of the ice cube is

$$\frac{x}{a} = \frac{\rho_{ice}}{\rho_{water}}. \quad (2)$$

The next step in calculation is awareness, oil also contributes to a buoyant force. If the density of oil is larger than the density of ice, then ice floats and the equation (2) is still valid, with density of oil replaces the density of water. However, if the density of oil is lower than that of ice, then one must recalculate. Data on the internet show that the latter should be true, however, experience demonstrates the opposite. Usually, accessible edible oil has lower density than ice, which is usually made from tap water where a lot of gas is dissolved and remains frozen as bubbles in the ice. Nevertheless, the density of ice can be increased by added sugar.

$$\rho_{ice} V_{ice} g = \rho_{water} V_{displaced\ water} g + \rho_{oil} V_{displaced\ oil} g \quad (3)$$

Using variables in Figure 5 yields

$$\rho_{ice} a = \rho_{water} x + \rho_{oil} (a - x) \quad (4)$$

and finally

$$\frac{x}{a} = \frac{\rho_{ice} - \rho_{oil}}{\rho_{water} - \rho_{oil}} \quad (5)$$

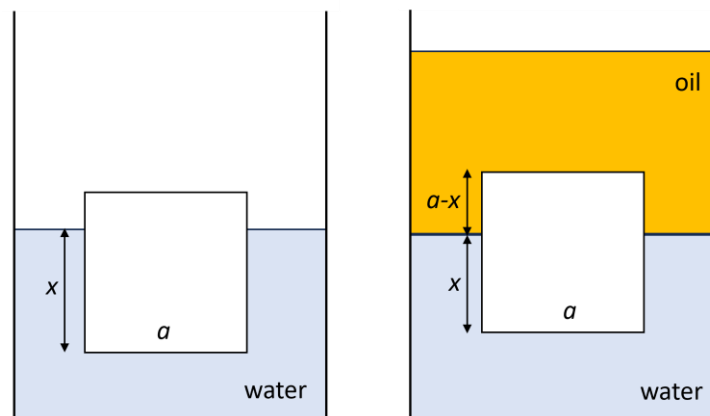


Figure 5: Variables in calculation of the position of ice

If values for densities are inserted, one realises that the ice must have moved quite high into the oil.

However, if one conducts this simple experiment by dropping the ice cube into the water and pouring oil over it, the results are far from the theoretical prediction. The ice remains almost entirely in water. When buoyant forces of two liquids are close, one must consider surface tension, which makes a significant contribution, as the molecules of oil and water strongly repel each other. The hydrophobic effect can be easily reduced by adding a small drop of dish soap.