Boat in the pool – lab work

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Abstract. This article describes a non-traditional lab focused on applying Archimedes’ principle in a situation that is, for students, new and unusual. Two main interconnected features of this lab are important. Firstly, it is not a “standard” lab experiment in which students are instructed to measure something and then to interpret results. Here, a very important element is prediction. Students have to predict the result first, calculate it using Archimedes’ principle, and only then do the measurement. Secondly, it is not the teacher who tells students whether their calculation is right or wrong, it is the experiment itself. This article presents the lab work itself (instructions and results), some methodological comments, and my experience in school.

1. Introduction
Archimedes’ principle is considered one of the most difficult topics in physics at lower secondary school. Many articles concerning methodology of teaching this law were published in various sources. Different approaches to teaching buoyancy are described in detail in [1]. The authors state several pedagogical practices which differ in the nature of associated inquiry processes:

Table 1. How the various pedagogical practices relate to one another in terms of intellectual sophistication and locus of control. [1]

| Discovery Learning | Interactive Demonstration | Inquiry Lesson | Inquiry Labs | Real-world Applications | Hypothetical Explanations |
|--------------------|---------------------------|----------------|--------------|------------------------|---------------------------|
| low                |                           | Intellectual Sophistication | high        |                        | student                   |
| teacher            |                           | Locus of Control          |              |                        |                           |

As you can see in the table, the most advanced form of inquiry is hypothetical inquiry (pure or applied). (Note: Authors of [1] use terms hypothetical inquiry and hypothetical explanations as synonyms.)

The lab “Boat in the pool” is an example of applied hypothetical inquiry where hypotheses are tested in an experiment. In this activity, students have to present their ability to transfer the skill of calculating buoyancy into the action of predicting the characteristics of a loaded vessel. Students need to use thinking skills to calculate given tasks and successfully demonstrate their knowledge of buoyancy.

A similar activity as in this article is mentioned in [2]. Students have to predict the maximum mass that a ship can hold without sinking. Students will then test their prediction by sailing their loaded ship. It is interesting that the authors have the similar method - students are not allowed to place “ships” into
the water prior to the test. However the present lab “Boat in the pool” is more difficult for students and requires deeper understanding of the problem.

I have a long-time experience with this lab. I give it to my students in the 9th class (about 15 years old) every year. I use it also as a part of a programme of the teacher education course in the Heureka Project [3]. Together about twenty groups – people from the age of about 15 to seniors – solved this problem in the last ten years. I found that regardless of the age of participants, their previous physics education or their experience with experiments, this lab work is rather difficult for them. In spite of it I think that for students it is very important to do it. More comments will be given later.

2. Instruction for the lab work

2.1. Necessary equipment
For each group: 2 beakers (glass or plastic, beakers should be cylindrical and should have different diameters), a ruler, a callipers for measuring the internal diameter of a beaker, a calculator, see Fig.1.

For the whole class: digital laboratory scales, access to a water tap.

![Figure 1. Necessary equipment for each group.](image)

2.2. Preparation
Students work in pairs (or in larger groups if necessary). If possible, no more than 7–8 groups should work in the classroom, otherwise some assistants would be necessary. I am afraid that one teacher is not able to organize and lead this lab work when more students work at the same time. The lab work takes about 1.5 hour (including closing discussion).

Each group gets two cylindrical beakers. Beakers could be different for different groups, this is even preferable. The broad beaker is empty (we call it a pool) and the narrow one (it will serve as a boat) contains some small amount of water, see Figure 2 (water could be dyed with tea). The contents of the boat may not be poured out during the work. Those beakers should be prepared in such a way that the boat could float in the pool when the pool is filled with water.

![Figure 2. Starting situation.](image)
2.3. Instructions for students
Each group has two beakers – a pool and a boat. You may not pour out the content of the boat and you may not fill the pool with water yet. You can use a ruler, a callipers, digital scales and calculator, nothing else.

Task 1. Calculate the draught of the boat when it floats in the pool (indicated by the letter \( p \) in Figure 3). After finding the first value (\( p \)) come with your beakers to the teacher’s desk, pour the water into the pool and measure the right values. When both values (calculated and measured) are (approximately) the same, you fulfil this task; empty your pool again and you can continue to the next task.

Task 2. Calculate how the surface of water in the pool rises after putting the boat into it (indicated by the letter \( s \) in Figure 3). Check your result experimentally.

![Figure 3. First two tasks.](image)

Task 3. Calculate the minimum amount of water (in centimetres) in the pool to allow the boat to float in it (it is shown by letter \( m \) in Figure 4). Determine the value of \( m \) without using the value of \( s \) from the previous task. Check your result experimentally.

![Figure 4. The third task.](image)

Task 4. Try to find a relation between the values of \( p \), \( s \), and \( m \). Give reasons for the relation.

3. Comments on the solution
Usually 1–2 groups of students are able to solve this problem without any help, about four groups need some “pushing” and several groups need a deeper explanation at least in a part of a task.

3.1. Comments on the first task – the draught of a boat when it floats in the pool
Students are able to find the draught usually without problems. They know that gravitational and buoyancy forces should be equal when the boat floats. They weigh the boat, so they know the value of the buoyancy force. From this force they calculate the volume of submerged part of the boat, and then they measure the area of the base of the boat and calculate the draught of the boat. Usually in about 5 minutes some group comes to the teacher’s desk and checks its calculation.

An exact calculation could proceed as follows (\( S_1 \) – area of the outer bottom of the boat, \( F_B \) – buoyant force, \( F_G \) – weight of the boat, \( \rho \) – density of water, \( V_{\text{boat}} \) – volume of the water displaced (= volume of the submerged part of the boat), \( m_{\text{boat}} \) – mass of the boat, \( p \) – draught of the boat):

\[
F_B = F_G
\]
\[ F_b = V_{\text{boat}} \rho g = pS_1 \rho g \]
\[ F_c = m_{\text{boat}} g \]
\[ p = m_{\text{boat}} / (S_1 \rho) \]

3.2. Comments on the second task – change of the water level in the pool after putting the boat into it

The second task is much more difficult for students. When helping them, I usually ask them to express the volume of water in the pool in both situations – without the boat (\( V_{\text{water1}} = S \ h \), \( h \) is the height of water in Figure 3a, \( S \) is the area of the bottom of the pool) and with the boat inside (\( V_{\text{water2}} = S \ (h+s) \) – \( V_{\text{boat}} \), see Figure 3b). From the equation – the volume of water remains the same – students express the value of \( s \). They find that the increase of the water level does not depend on the initial amount of water.

Sample calculation (\( S \) – the area of the inner bottom of the pool, \( h \) – the height of water in Figure 3a, \( s \) – increase of water, \( V_{\text{water1}} \) – volume of water in Figure 3a, \( V_{\text{water2}} \) – volume of water in Figure 3b):

\[ V_{\text{water1}} = V_{\text{water2}} \]
\[ V_{\text{water1}} = Sh \]
\[ V_{\text{water2}} = S(h + s) - V_{\text{boat}} = Sh + Ss - V_{\text{boat}} \]
\[ V_{\text{boat}} = Ss \]
\[ s = V_{\text{boat}}/S \]

This second task could also be solved in the following way. We know (according to Archimedes’ principle) that putting the boat into the pool should have the same effect on the water level as pouring the same mass of water (as the boat) into the pool. The calculation of the change of the level of water is then easy.

I would like to emphasize that it is necessary to ask students for their solution in this task, not only let them experimentally check their calculation. Students usually mistakenly assume that this “poured” water fills only the space around the boat between the two beakers. Starting from this incorrect assumption leads to following incorrect result:

\[ V_{\text{boat}} = (S - S_1)s \]
\[ s = V_{\text{boat}}/(S - S_1) \]

Sometimes the difference between right and wrong solution is so small (if the pool has considerably larger diameter than the boat), that it could be (incorrectly) assigned to inaccuracy of measurement.

3.3. Comments on the third task – minimum amount of water in the pool for a boat to float in it

Students make a similar consideration as in the second task when solving the third task. They have to take into account that water in the situation in Figure 4b is only around the boat, not below it. The key idea in this task is that the depth of water in the pool in this situation (Figure 4b) should be the same as the draught of the boat in the first task.

Sample calculation (\( m \) – the minimum amount of water):

\[ Sm = (S - S_1)p \]
\[ m = (S - S_1)p/S \]

3.4. Comments on the fourth task – finding a relation between the three values

Students who really understand what they are doing usually very quickly find the solution of the last task. They find that \( p = s + m \). Sometimes they try to use this relation for finding the value \( m \). Therefore I give them a condition not to use the value of \( s \) in the task 3.
4. Comments on the whole activity
The discussion after measuring is a necessary part of the lab. The teacher should ask some students to explain the last task and he or she should (together with students) evaluate their work during the lesson.

As I mentioned before, this lab is difficult for students, some of them cannot solve it without some help. I have many years of experience that it is very important for students (and interesting, too) to come with some result to the teacher’s desk, to pour the water to the beaker, to measure the real value and to check their calculation. They check their solution by themselves; their results are independent of the teachers’ decision. There are only few situations in school lessons when students can check their calculation using an experiment, this lab work is one of them.

A similar atmosphere during checking the solution is common when this lab is done by teachers (see Figure 5). My experience proved that teachers and students have very similar difficulties with this lab. That is why I strongly recommend all teachers to try it by themselves before using this task with students.

Figure 5. Teachers check their solution.

5. Conclusions
The key points of this lab are:
- hypotheses made from (not easy) calculations
- checking hypotheses using experiments and measuring
- repeating this process if necessary (if the result is wrong)
- the result is independent on teachers’ decision

In my experience this lab is interesting for teachers in the Czech Republic and I hope it is interesting also for teachers in other countries.

References
[1] Wenning C J, Vieyra R E 2015 Teaching High School Physics vol 1 (Google Play Edition) p 83
[2] Haug J Investigating Buoyancy 2018 Calculating the Maximum Load of a Ship MnSTEP Activities
[3] The Heureka Project 2018 http://kdf.mff.cuni.cz/heureka/en/