Teaching Archimedes' principle

to sixth graders without teaching mass, density, pressure, volume or buoyancy

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Flotation is usually taught in Indian schools after students have been introduced to the concepts of mass, density, pressure, volume and buoyancy. This paper describes an attempt to teach the principle of flotation to a class of sixth graders—who had not yet been taught these concepts—so they could understand (and, perhaps, arrive at) Archimedes' principle. Using a modified version of the Predict, Observe, Explain (POE) pedagogy called PROVE (Predict, Reason Out, Verify), this paper describes how students began to use a process of iterative reasoning to develop their conceptual understanding of the law of flotation of objects, and how some of them came very close to understanding the principle, without the introduction of the necessary concepts. It also suggests the use of such pedagogy for the teaching of other concepts in science, to empower students to *first think their way through complex ideas* **without getting bogged down by definitions and technical terms.**

INTRODUCTION

This paper describes the researcher's experience in teaching and exploring Archimedes' principle with a class of thirty-five sixth graders, in two lessons of eighty minutes each. Since the researcher was a visiting faculty member in a residential school located in North India, the class was taken after discussing the current level of the students' knowledge with their regular science teacher. [This paper refers to their usual science teacher as the 'current teacher', and the researcher as the 'visiting teacher'.]

Beginning with an overview of research literature in this field, the paper outlines the research purpose, and then describes the methodology employed during the lessons, as well as the interaction between the visiting teacher and the students during the two lessons. Finally, a brief assessment of the learning outcomes of the students at the end of the two lessons is provided.

OVERVIEW OF LITERATURE

Inhelder and Piaget (1958) first reported on students' ideas about flotation. Through the use of classification activities to help students formulate rules that would determine which objects would float or sink, they reached the conclusion that advanced reasoning skills are needed to develop such rules, and that students need to identify the relevant variables as well as make connections between them. In addition, they concluded that an understanding of ratio and proportion was also required by the students, as well as a certain degree of abstract reasoning. Considerable research on the pedagogy of flotation has since been conducted by other researchers.

The phenomenon of floating and sinking offers a valuable opportunity for learners to connect observable events with abstract, unseen causes. Bliss (1995) argued that this is precisely the difficulty for young students. Rowell and Dawson (1977a, 1977b) worked on developing students' understanding of density, which was deemed to be a prerequisite for understanding the law of flotation. In their study, Gürdal and Macaroglu (1997) assert that "before teaching the phenomenon, concepts of mass, weight, volume and density, and their differences, should be clarified." Macaroglu and Senturk (2001) explored fourth grade students' understanding of flotation and sinking and found that students' misconceptions prevented them from identifying which object would float and which would sink. Unal (2008) also asserted that:

> *Among researchers who have investigated students' understanding of flotation, there is consensus that most of the students' difficulties about flotation stem from erroneous or incomplete ideas about underlying concepts such as volume, mass, density, force, and pressure (Halford et al., 1986; Jain, 1982; Mullet and Montcouquiol, 1988; Smith et al., 1985). This also shows that students retain their ideas in a fragmented manner (Haidar, 1997; Çalık, 2005).*

While Raghavan, Sartoris and Glazer (1998) reported that:

> *Because students tend to confuse mass with volume and force with pressure, it is difficult for them to understand buoyant force or to relate the weight of an immersed object to the weight of an equal, imagined volume of fluid. Similarly, students who do not comprehend the intensive qualities density and pressure, both of which are ratios, are unable to compare the density of an immersed object with that of the surrounding fluid or to understand why such a comparison is significant.*

There appears to be general agreement between researchers that an understanding of the law of flotation warrants prior understanding of the distinction between weight and density. Smith, Snir and Grosslight (1992) found (and cited considerable supporting literature to demonstrate) that sixth and seventh graders *do not differentiate* between the concepts of weight and density. They designed a curriculum to facilitate this understanding in sixth and seventh graders and found that those children who initially had some idea about the two concepts were the ones who were helped the most by their curriculum.

This emphasis on defining terms like mass, density, pressure and volume before learning Archimedes' principle is not restricted to fourth to seventh graders alone. Heron, Loverude, Schaffer and McDermott (2003) have reported how Archimedes' principle was taught to undergraduate students *after* defining concepts like mass, density, pressure and volume.

RESEARCH PURPOSE

The intent of this research was to find out if it is possible to get sixth graders—who have not yet been formally taught the concepts of mass, density, pressure, volume and buoyancy—to understand (and, perhaps, arrive at) Archimedes' principle. The entire lesson was therefore presented without using any of these terms.

METHODOLOGY

The current science teacher confirmed that the students had not yet been formally taught the definitions of density, pressure or volume. Since the intent was to see what children thought and understood about flotation and sinking, the two lessons were planned and presented by the visiting teacher with an emphasis on the children's thinking. This is summarised below in Table 1.

Table 1. Design of lessons.

STEP	PLANNING	PRESENTATION/DELIVERY	CONSISTENCY IN THINKING
1	Make a collection of fruit and vegetables, such as: cucumbers, carrots, pumpkins, green coconuts, husked coconuts, pineapples, apples, pears, bananas, potatoes and ginger.	Divide the class into groups of three (two groups had four students each). Ask students to a. select a fruit or vegetable, and b. predict whether it will float or sink. During discussion with each group, allow students to change their prediction if a group member convinced them otherwise.	Explicitly explain to the class that in this lesson they are going to 'think like scientists' and that scientists sometimes make errors before arriving at a definite conclusion; so they, too, should feel free to go back and forth in their reasoning (iterative thinking process).
2	Prepare a template to record observations (see copy in appendix).	Encourage the groups to systematically record their predictions on the template.	Elicit a hypothesis from each group as to *why* they think the fruit or vegetable will float/sink, and ask them to record this on the template *before* setting out to verify the prediction.
3	Arrange six buckets filled with water in widely spaced locations outside of the classroom.	Take the groups outdoors to allow a. independent testing of above predictions, and b. systematic recording of their observations on the template.	After testing four or five fruits/vegetables, revisit their reasoning and draw out from each group a 'rule' that allowed them to generalise floating/sinking of fruits/vegetables.

Note: The experiments were conducted during the first lesson, and discussed in the second (two days later).

Figure 1. Children seeing how a banana and ginger float. Photo courtesy Neeraja Raghavan.

TESTING PREDICTIONS

Since the students were asked to record their prediction on the template provided, and then *write out their reason for thinking so,* a variety of predictions emerged, such as:

- if it is big in size, it will sink;
- if it is heavy, it will sink;
- if it has a lot of air in it, it will float; and
- if it has a hollow space within, it will float.

After making their predictions, the groups went outdoors to conduct their tests. There was much excitement as they discovered whether they were either 'right' or 'wrong'. Each group tested a minimum of five items.

Figure 2. Children observing cucumber floating. Photo courtesy Neeraja Raghavan.

CONSISTENCY IN THINKING

In the second lesson, the teacher worked through the following steps with the class.

- Bringing the attention of the students to contradictory statements (like heavy objects will sink, but a coconut has been found to float)
- Drawing out from each group a final rule for flotation, after they were helped in ruling out inconsistencies in their iterative process
- Drawing out ideas from the quieter students and thus empowering them to contribute freely

Each group was then asked to develop, and share with the whole class, a rule that applied to the floating and sinking of *all* objects. As each group cited different properties that they believed caused flotation—like size, weight, 'containing air', 'having a hollow inside'—they were promptly shown a counter example by another group. Almost all the children were observed to be actively thinking and challenging each other's hypothesis. The visiting teacher drew the following table on the board and filled it in as their discussion generated entries.

Table 2. Responses of students after conducting their flotation tests with fruit and vegetables

WE MADE THE RULE THAT ...	SO WE EXPECTED THAT ...	BUT WE FOUND THAT ...
Fruit and vegetables with seeds float	Ginger will not float	Ginger floated
Heavy fruit or vegetables will sink	Coconut will sink	Coconut floated
Fruit or vegetables with a hollow space inside will float	Cucumber will not float	Cucumber floated
Small fruit or vegetables will float, large fruit or vegetables will sink	Pineapple will sink	Pineapple floated
Leafy fruit will float	Pineapple without its leaves will sink	Pineapple without its leaves floated

Figure 4. A leafy pineapple is half submerged. Photo courtesy Neeraja Raghavan.

Figure 3. Coconut surprises children by floating. Photo courtesy Neeraja Raghavan.

Figure 5. Children discover that sweet lime floats. Photo courtesy Neeraja Raghavan.

POSING AN OVERARCHING QUESTION

After the group presentations and resulting discussion, the class agreed that there was not enough of a consensus to arrive at *one consistent law* for flotation.

The teacher then described how a nail made of iron sinks in water, but a huge ship made of iron/steel and wood does not sink and posed the question of why this should be so. Some students tried to explain this by proposing that the nail was pointed and so it sank, but the ship was flat so it floated. However this drew a counter question from another student who stated that: "Ships also have pointed edges; they also cut the water as they move forward ..." Another student posited that the fuel in the ship keeps it moving, and that is why it floats. "Do stationary ships sink?" countered the teacher. This sort of exchange set the class thinking.

The visiting teacher then described the well-known problem posed to Archimedes by King Hiero—of deciphering whether the royal goldsmith had cheated the king of some gold while making the new crown. Although the completed crown weighed exactly the same as the pure gold had, the king suspected that the goldsmith may have cheated him of some gold. What was more, Archimedes was asked to solve this mystery *without destroying or damaging the crown in any way*. The teacher also described how, Archimedes (a large man), after immersing himself in a tub of water, noticed that he had pushed away some water.

The visiting teacher informed the class that she was going to explain exactly what Archimedes had discovered, and the law of flotation, but that if any of the students wished to think this through for themselves, they could leave the class so as to enjoy the fun of solving the problem themselves. Seven students opted to solve it for themselves and left the class.

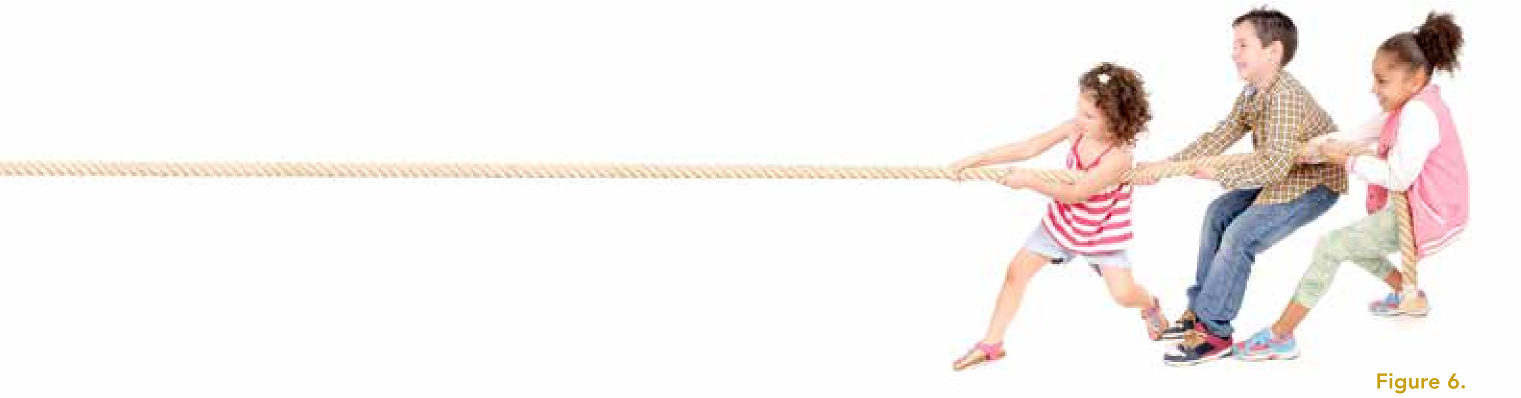

Figure 6. Tug-of-war as it is commonly played.

The visiting teacher made a sketch of two teams playing tug-of-war, and asked the class which team usually wins such a tussle. Almost immediately, all agreed that *the team that pulled more strongly* would win. The teacher used this explanation to draw their attention to how whenever there are two opposing forces *the final direction of movement is determined by the stronger force*.

The teacher then illustrated how the same law could apply just as well in the vertical direction.

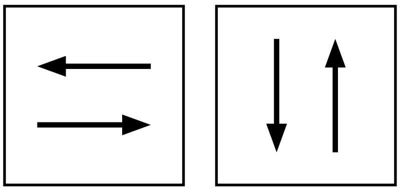

Figure 7. Teacher's illustration of how the law could apply in the vertical direction.

Sketching a ball half immersed in a vessel containing water, the teacher asked the class what force could be pulling this object downward. All the students responded: "Weight!". The teacher explained that when a ball is immersed in water, some water is pushed down to make space for the part of the ball that goes into the water. This 'pushed away water' pushes the ball up, so if the ball *pushes away lots of water*, it gets a forceful push up. Whether it stays up or sinks, the teacher explained, is determined by whether the downward or upward force is stronger—just like the winner of the game of tug-of-war.

All the students appeared to understand this. (Note: terms like mass, density, pressure, volume or buoyancy had not been used in the lessons.) The teacher explained that Archimedes had gleaned that while pure gold would push out a certain amount of water, *a mixture of gold and another metal* would have pushed out a *different amount of water*. Rather like a new team being constituted to play tug-of-war, the teacher explained, the strength of the two opposing forces would be impacted by this mixture of two metals. The students appeared satisfied with this reasoning.

"Did the goldsmith actually cheat the king?" asked the children, and they were told that yes, indeed, Archimedes discovered that the goldsmith had cheated the king.

FOLLOW-UP WITH THE SEVEN STUDENTS WHO OPTED TO SOLVE THE PROBLEM FOR THEMSELVES

When the visiting teacher left the classroom at the end of the lesson, she met with the seven students who had opted to think through the problem for themselves. They announced that they had solved it. Just like Archimedes pushed away some water inside the tub when he sat in it, the gold would do the same, they explained. All that Archimedes had to do was to first immerse a lump of gold in the water and see how much water it pushed away. Then, he should have removed the gold and immersed the crown instead. He should again have noted how much water was displaced. Comparing these two, he would know whether or not the crown was made of pure gold.

The teacher then asked if the *amount* of pure gold that was immersed in water mattered: and if it did, how much should be immersed?

"The same amount of gold that the king gave the goldsmith to make the crown," stated one student, empathically.

It was interesting that these seven students had progressed this far in reasoning out the law of flotation, *without any idea of concepts like mass, density, pressure and volume*. Of course, their reasoning was still incomplete in quantitative terms, but their intuitive manner of thinking this through was a revelation for the visiting teacher—who had never seen sixth graders think through flotation like this before.

ASSESSMENT OF LEARNING THE DAY AFTER THE SECOND LESSON

A day after the second lesson, the following question was written on the blackboard by the current teacher: "Why do some objects float, while others sink?"

About half of the class wrote explanations that floating or sinking is determined by the stronger of two opposing forces: (1) the weight of the object pulling it down, and (2) the upward force due to the displaced water pushing the object. The responses of the other half of the class ranged from a confused articulation of the above principle to some mix of the rules shown in Table 1.

The seven students who opted to think the principle through for themselves were interviewed (and their responses video-recorded) so as to better understand their flow of thoughts as they had arrived at the answer.

Firstly, they were able to describe how Archimedes must have solved the mystery of the purity of the gold crown. "We felt gold would sink, because it is heavy, but then we asked why a ship floats even though it is heavy. We felt it could be due to its shape, which … just like (fat) Archimedes pushed water out of the bathtub … the ship also must be pushing out a lot of water … so we felt that pure gold would displace some water, while mixed gold would displace a different amount of water."

However, the group of seven were unable to articulate the principle of flotation as being a consequence of *two opposing forces*, having missed that part of the explanation by the visiting teacher. They were more focused on their discussion of the problem posed to Archimedes—and the fact that they had opted to solve it by leaving the class when they did.

Secondly, it was found that they were *cognisant of their collaborative effort*, as they described the flow of their discussion thus:

> *"One by one, words came into our minds … together we formed the sentences … we had to guess if the crown was made of pure gold or not. Just like creating a building … one of us laid the base of the discussion. Then everyone made the base stronger. Then, two of us said: 'let's go deeper and get to the top of the building' … so we thought and thought. I was saying something and he was saying something, and then at last we joined two sentences, and we got the answer!"*

Doise and Mugny (1984) have proposed that for peer interaction to result in progress, the peers must jointly construct a superior solution. From the narrative of their process of discussion, it is evident that such an event did occur (and was noted) in this group.

LIKELY FLOW OF FURTHER LEARNING

The class had reached a certain level of understanding about the two opposing forces that are set into play upon immersing an object into a liquid. It is this researcher's view, that this would have been the opportune time to demonstrate how, by changing the shape of an object, we can control whether it floats or sinks. This could have drawn them closer to understanding why an iron nail sinks but a steel ship floats. Also, this would be the right time to introduce terms like density, volume etc., to allow further exploration into the influence of the density of the fluid.

DISCUSSION AND CONCLUSION

The process of drawing out children's existing ideas before teaching them a concept has been successfully tested by several researchers over the years. Driver, Leach, Millar and Scott (1996) found that children expressed views similar to those put forth by the students in this study, while trying to guess why some things floated while others sank. Effecting conceptual change has been found (by Unal, 2008; Case and Fraser, 1999; Freedman, 1997; Kahle and Damnjanovic, 1994; and Wenglinsky, 2000) to be much more successful through hands-on activities than traditional teaching.

The PROVE pedagogy employed in this study was also found to be successful in provoking iterative thinking and deductive reasoning. The seven students who thought the problem through seemed poised for a definition of density, a term that they had not yet articulated but seemed to have arrived at intuitively. Thus, this study suggests that the definition of density is better introduced *after* such an exploration, rather than at the start—as suggested in the literature. Since about half the class had shown their understanding of the basic principle of flotation, this convinced the visiting teacher that terms like density, pressure, volume and buoyancy *need not first be defined* in order to explain why things float or sink. Indeed, this experience even suggests that such definitions are, perhaps, best left for later: *after* the students have acquired a simpler understanding of flotation. That such an intuitive grasp is even possible was this researcher's discovery through this study. [As for the other half of the class, a revisiting of their initial rules in light of the two opposing forces (that they had understood) could, perhaps, have helped resolve their confusion.]

Further, the provision of an option to the class to *think the problem through for themselves* proved to be an enriching step—for those who took that option not only arrived at a method to resolving whether the crown was made of pure gold, but also realised the power of collaborative discussion.

It is the view of this researcher that the following three elements are worth including in a science lesson.

1. Preceding the introduction of definitions and technical terms with *an experiential engagement of the students with the concepts* that need to be learned. This sequence is intuitively appealing to the learner and is likely to facilitate sustained engagement by, and enjoyable learning for, the students. Following this up with definitions of terms such as mass, density, pressure, volume, etc. would probably be effective, as the learners would then be more ready to receive and understand such definitions.
2. Drawing the learner into making predictions and giving reasons for those predictions so as to discover existing assumptions has a twofold consequence: Once a prediction is made, the student is 'hooked', so to speak, as there is great eagerness to be proved 'right'. Secondly, the articulation of the underlying reason for that prediction necessitates the emergence of existing assumptions even as it paves the way for the later bringing in of consistency in scientific argumentation.
3. Giving students the option of thinking the problem through for themselves opens up a space for the motivated students to take up a challenge and try their hands at solving it. It also allows them to experience collaborative learning and realise the power of discussion.

It is this researcher's observation that, although the students found the science experiment engaging, the lasting power of such an experience can, of course, only be seen after some time has elapsed. The manner in which questions continued to buzz well after the lessons concluded does indicate the intensity of the students' involvement.

ACKNOWLEDGMENTS

The researcher wishes to thank the students of Class VI, the teachers and the principal of Rajghat Besant School, Krishnamurti Foundation India, Varanasi for giving her this opportunity.

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APPENDIX

Prove template

PREDICT REASON OUT VERIFY PROVE!

Name of fruit/vegetable given to you:

....

Question:

Will this vegetable/fruit float in water?

....

....

....

Prediction:

....

....

Reason for above prediction:

....

....

Please begin your experiment only after filling in the above two items.

Verification:

....

....