Approching the concept of atmospheric pressure : an interview based on Torricelli's barometer

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Abstract

The ambition of our study is to highlight spontaneous reasoning involved in hydrostatic problems and to identify key steps in students' learning processes that could be useful for teaching hydrostatics. More specifically, this article aims at observing and modifying the spontaneous reasonings involved in the interpretation of Torricelli's experiment (the mercury barometer). Our study consists of three forty-minute interviews during which several experiments are either performed or presented to a student. The sequence of experiments has been designed by taking into account the History of Sciences, especially regarding the role of the atmospheric pressure. The analysis of the interviews confirms a marked tendency towards localized reasoning established in previous research, while clarifying its nature : according to the students, the test-tube mercury either floats on that of the container or is drawn upwards by the effect of capillarity. Our study also modulates previous research about the concept of vacuum, both in itself, and applied to Torricelli's experiment and suction pumps: whereas they consider that this vacuum cannot physically exist, they spontaneously use the concept to interpret and predict the phenomenon of suction. Also, the students retain a notion of "vacuum" corresponding to a total absence of matter. The interview designed and carried out for the experiment aims not only to observe students' difficulties, but also to modify them. For two of the three students, the sequence does indeed contribute to an understanding of the significance of the role played by the air surrounding the tube. This study is also an interesting example of the role that History of Science can play for Teaching Sciences in *anticipating* reasoning strategies or difficulties on one hand and *providing ideas* to modify reasoning on the other.

Introduction

The ambition of our study is to highlight spontaneous reasonings involved in hydrostatic problems and to identify students' key learning steps, in order to contribute to the understanding of problems involved in teaching hydrostatics. In order to do this we chose a problem which is both classic and rich: Torricelli's experiment.

Torricelli's barometer experiment consists of a one-meter glass tube filled with mercury, stood upside-down in an unsealed container also filled with mercury. This experiment is a common illustration of the hydrostatic equation $\Delta P = - \rho g \Delta h$. However, as is the case in most of the other problem of hydrostatics, several of its more complex physical characteristics are masked by the mathematical simplicity of this equation.

The aim of this study is firstly to observe students' strategies in their interpretation of Torricelli's experiment. Given previous research results which strongly suggest that students fail to understand the experiment from a systemic point of view, we aim to identify more closely their localized reasoning. Secondly, we aim to develop a strategy which will allow teachers to modify their students' reasoning, leading them towards a systemic point of view.

Three individual interviews were carried out. They consisted of several experiments which were either presented to the students or performed in front of them. The sequence of experiments was designed by considering not only previous research about students' spontaneous reasoning concerning Torricelli's experiment, but also the historical development of the question, and of scientists' responses.

Historical guideline

Ancient Greek scientists considered the phenomenon of suction to be a consequence of the Aristotelian doctrine, 'Nature abhors a vacuum'. However Galileo reported, in *Two new sciences (1638)*, that a suction pump could not lift water more than about 10 meters.

In 1644, Evangelista Torricelli transformed the technical problem of the water-pumps into a scientific question by proposing a new experiment using mercury. Torricelli suggested two new hypotheses : firstly, that the space above the mercury is a vacuum; secondly, that air has mass. These hypotheses led to the interpretation that it is the weight of the air outside, pushing on the mercury in the container, which maintains the height of the column.

Each of Torricelli's two assumptions raised controversies among the scientific community and several experiments were designed to assess them. These consisted in modifying the environment of Torricelli's device: in Pascal's experiment (1648), it is placed at different heights in the atmosphere [1]; in Boyle's experiment (1660), it is performed in a suction device [2]; in Mariotte's experiment (1676), it is placed at different depths in water [3]. It is the explicit analogy between water and air established in Mariotte's experiment which definitively confirms Torricelli's interpretation.

Research background

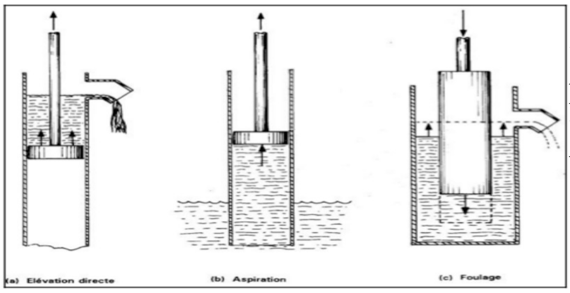
Several studies analyse students' reasoning concerning aspects of the experiment. The unifying concept of "fluid" doesn’t always seem to be operational for students: although most rightly assert that pressure increases with depth in liquids [4], some incorrectly think that atmospheric pressure increases with altitude [5]. However, some difficulties arise which apply both to liquids and gases: the pressure in a fluid is usually confused with the forces exerted by the fluid [4]; pressure is often associated with the volume of fluid surrounding an immersed solid, and not only with depth (or altitude) [6], and its effects are widely seen as directional (usually down) [7, 4, 8]. “Vacuum” is another problematic concept for students. While a high percentage of young people struggle to admit the existence of an absolute vacuum [9], any degree of “vacuum” is commonly considered to have mechanical properties, most importantly, that of aspiration [10, 11].

Elements of the History of Science can be useful for anticipating students' difficulties and providing ideas for teaching sciences. In 2009, Hosson & Caillarec [12] used Pascal's experiment to study students' understanding of Torricelli's experiment. They asked the students why the height of the column of mercury changed at different altitudes. Over three-quarters of the 128 students surveyed did not explicitly take the air outside the device into account in their explanation. Indeed, instead of using a systemic point of view, they tended to use localized reasonings, based on the following elements of the experiment: the content of the space above the mercury, which, according to the students, would dilate or contract; the column of mercury which would dilate or contract, like in a thermometer; and the mercury in the container which would support the mercury in the tube. In the end, as was the case for scientists in the 17th century, the study found that Pascal's experiment alone was not sufficient to convince students of the mechanical influence of the air.

Hence, two questions emerged: firstly, how to confirm and complete these results, and secondly, how to lead students to take into account the mechanical effect of air. Like the previous study, ours will be based on a framework drawn from the History of Science: this time, using Boyle's experiment to illustrate and clarify Torricelli's experiment to students.

The interview

An interview was designed based on a series of experiments, either performed or presented to the student. This series was conceived to distinguish the relevant variables (density of the liquid, maximum height of the column of liquid, outside air) from the non-relevant ones (length of the tube, size of the container), and to demonstrate the relationships between the relevant variables. The series of experiments presented to the three students were identical, as was the process used to elicit responses at each step. This process consisted of a first stage, designed to identify students' spontaneous responses, in which an experiment was set up and they were asked Q1) to predict its results, and Q2) to explain their prediction. The experiment was then performed, and a second set of questions was asked, aiming to lead them to modify their spontaneous reasoning: Q3) to observe the experiment, Q4) to compare their observation to their prediction, and Q5) to interpret this comparison.

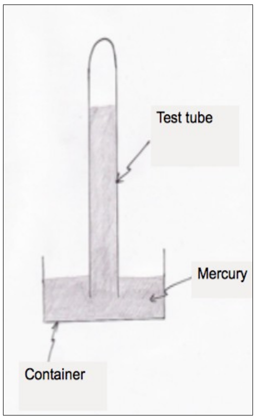


The question to be resolved during the interview is presented at the beginning. Three different types of pumps are presented and it is stated that it is impossible for the second one, a suction pump, to raise water above a certain height (which is not given at this stage). The student is then asked why; all the following experiments are designed to develop a systemic understanding of this phenomenon.

First, the suction pump is illustrated experimentally using a syringe. The student is asked the series of questions Q1-Q5, beginning with Q1 : “What will happen if the syringe piston is pulled?”

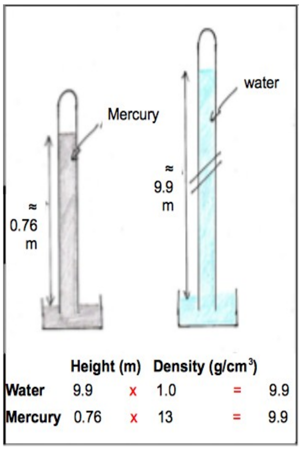
Torricelli's experiment is then presented, using water instead of mercury. The key Q1 is : “What happens if the tube filled with water is stood upside-down in a container of water?”

The student is asked what will happen if the tube is stood upside-down in a much smaller container. The following Q1 is: “What will happen if the experiment is performed with longer and longer tubes?” The answer is not given at this stage.

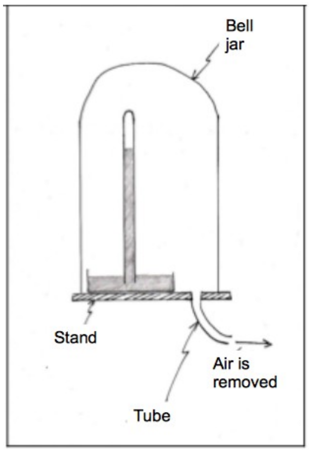


The following step asks the student to predict the result if the water is replaced with mercury. After the presentation of the actual observation the student is asked: “What is above the mercury?”

The following stage asks the student to combine his previous findings to make a new prediction. The diagram of Torricelli's original experiment, using mercury, suggests the following Q1 : “Do you think that, as for the mercury, the column of water will stop at a maximum height?”
The student is asked whether the column of water is taller or less tall than the column of mercury.



The final experimental step concerns the influence of modifications of the air pressure (Boyle's experiment). Q1: "What will happen if there is more / less air inside the bell jar?"



This qualitative approach is followed by a quantitative complement in which the influence of the air is highlighted thanks to a simple calculation inspired by the hydrostatic equation; the student is asked what physical element could be the same in both experiments.

In the last step, we come back to the initial questions. The first of these was : "What is the height limit for suction pumps?" ; the second was "How can the limitation of the suction-pumps be explained?"

The interview was carried out with three students. Having based the outline of the interview on anticipated errors drawn from previous studies, most importantly those of Hosson & Caillarec [12], we selected students of the same level in order to remain coherent with these results. The three students are third-year University students of primary teaching. They all studied the concept of pressure in upper secondary school and hydrostatic laws during their first year of university.

Results and discussion

A first series of results confirms previous results established by Hosson & Caillarec [12]: As in their previous research, none of the students surveyed here spontaneously mentioned the effect of the air outside the device; they also preferred local reasoning to a systemic approach. More specifically, during Boyle's experiment, we confirmed that students explained the phenomenon by suggesting a dilation / contraction of the column of mercury or of the matter in the space above the column.

Our study focussed on identifying different forms of local reasoning:

- As regards interpretations centred on the column of mercury, one of the students explained that water rises higher than mercury because the "*cohesive force*" between glass and water is stronger than that between glass and mercury. This interpretation brings to light a confusion between Torricelli's experiment and the notion of capillarity.
- With regard to the explanations centred on the mercury in the container, two students considered that as the liquids in the tube and the container are the same, their density is the same, and thus the column of mercury does not sink. This interpretation highlights a confusion between Torricelli's experiment and Archimedes' principle.
- Moreover, all three students predicted that the water inside the tube would overflow when the tube was stood upside-down in a much smaller container. This prediction reveals a misunderstanding of the role of the liquid in the container, probably due to a confusion between the properties of static liquid and those of solid matter.

This series of results highlights students' willingness to refer to different phenomena of fluid mechanics, (including Archimedes' law), whose limits, however, they do not perceive clearly. They are heavily influenced by their prior knowledge – even when it is imperfectly understood – and attempt to use known patterns in order to interpret an unfamiliar phenomenon.

Another series of results modulates previous research about the concept of vacuum, both in itself, and applied to Torricelli's experiment:

- Previous research suggests that students struggle to admit the existence of an absolute vacuum [9]. Our research confirms this idea and attempts to identify the nature and origins of this difficulty. We thus asked them to define a vacuum; the three students responded that "*a vacuum is when there is nothing*". This conception is inconsistent with the scientific point of view. Indeed, for example, the space above the column of mercury - usually qualified as *a vacuum* - is actually mercury gas whose particle density is around 10^{13} atoms/cm^3 - extremely dense compared to the "vacuum" in a particle accelerator, where the particle density is around 10^7 molecules/cm^3. It seems that students do not grasp the concept of partial vacuum, but represent it as a total absence of matter.

- Studies concerning younger students found that properties such as suction were attributed to vacuums [8]. While this was not precisely repeated in our study, we did notice that students spontaneously used the concept of a vacuum to justify the suspension of the column of liquid when there is no space above: in the case of the syringe, one of the students explained that "*when the piston is pulled, an empty space is created, but it is instantaneously filled with water"*. Surprisingly, however, when an empty space actually *is* observed in Torricelli's experiment with mercury, it was hard for the three students to admit that was a vacuum. In the end, whereas for the Greek scientists 'Nature abhors a vacuum', it seems that for the students, 'Nature *forbids* vacuum' : it is an "impossibility" which physical systems must "work" to avoid. The concept is seen as artificial, although students admit that it allows the prediction of correct results.

This study also suggests that a "teaching interview" like this one, drawing on the History of Science for its design, could also be an effective tool for leading students to modify their initial responses. Whereas before the presentation of Boyle's experiment, the three students used local reasoning to interpret Torricelli's experiment, after Boyle's experiment, two of the three students were finally able to apply a systemic point of view: "*If there is more air inside the bell, the pressure will increase; thus, the air will push on the surface of the liquid in the container and the liquid will be pushed up inside the tube*". The third student, while concluding that air must play some role, was not able to interpret rightly Torricelli's experiment.

This discrepancy between the first two students and the third merits further analysis. Indeed, these first results suggest that there may be a parallel between scientific developments in the 17th century and students' approaches. Indeed, in both cases, there seem to be pre-existing conditions (correct understanding of the nature of vacuum, ability to apply a mechanical approach) to the understanding of Torricelli's experiment. This hypothesis will require further examination, either by a more specific analysis of the interviews already conducted, or by a survey of a greater number of students.

Conclusions and perspectives

Our study provides several interesting analyses of spontaneous reasoning that could be useful for teaching not only Torricelli's barometer, but also hydrodynamics:

- in order to interpret Torricelli's experiment, the students used spontaneous reasoning inspired by their previous academic knowledge. Although this is a common and a productive learning strategy, it also causes misunderstandings. In terms of teaching, this suggests that in order to explain how Torricelli's experiment works, it could be useful to clarify why it is neither an example of floating or of capillarity. More generally, it suggests that the comprehension of a phenomenon could perhaps be aided by a comparison with others which produce similar results, but are based on fundamentally different principles.

- As the concepts of vacuum and suction occur frequently in studies of hydrodynamics, it is important to be aware of the fact that these notions often remain difficult for students. Two main ideas emerge. Firstly, students are ill equipped to accept the idea of a partial vacuum. Secondly, the notion of “suction” remains, suggesting to students that a vacuum “pulls” fluids, rather than a more correct interpretation in which it simply “pushes” less than its environment. This seems to suggest that an approach to hydrodynamics would benefit from a better understanding of the vacuum.

Concerning the effects of the interview, we show that the designed series of experiments decisively modify the spontaneous reasoning of two of the three students, leading them to adopt a systemic point of view. Hence two questions emerge: why is Boyle's experiment decisive for one student and not for the other? Could there be a relationship with the effects of Boyle's experiment on the 17th century scientific community?

A detailed comparison between each step of the three interviews and a specific study of the historical context of Boyle's experiment should allow us to answer these questions soon.

References

[1] PASCAL, B., *The Physical Treatises,* (Columbia University Press, New York, 1937).

[2] BOYLE, R., *New experiments physico-mechanical touching the spring of the air and its effects,* (London, 1660).

[3] MARIOTTE, E., *Nature of air*, A Source Book in Physics (McGraw-Hill, New York, 1953).

[4] KARIOTOGLOU, P. & PSILLOS, D., *Pupils' pressure models and their implication for instruction,* Research in science and technological education **11**, 95-108 (1993).

[5] TYTLER Tytler, R. T., *Students' conceptions of air pressure: Exploring the nature of conceptual change,* International journal of science education **20**, 929-958 (1998).

[6] VIENNOT, L., *Teaching physics,* (Springer, USA, 2003).

[7] ENGEL CLOUGH, E. & DRIVER, R., *What do children understand about pressure in fluids?,* Research in science and technological education **3**, 133-144 (1985).

[8] SMITH, P. S. & FORD, B. A., Project Earth Science: Meteorology, Arlington, VA: National science teacher association (1996).

[9] NUSSBAUM, J., *The particulate nature of matter in the gaseous phase,* in R. Driver, E. Guesne & A. Tiberghien (eds.) Children's ideas in science, (Open University Press, London, 1985), 124-144.

[10] SÉRÉ, M. G., *The Gaseous State* in R. Driver, E. Guesne & A. Tiberghien (eds.) Children's ideas in science, (Open University Press, London, 1985), 105-123.

[11] DE BERGE, K. C., *Students' thinking in relation to pressure-volume changes of a fixed amount of air: The semiquantitative context*, International journal of science education **14**, 295-303 (1992).

[12] de HOSSON C. & CAILLAREC B. (2009). Students' ideas about Blaise Pascal experiment at the Puy de Dôme Moutain. *Latin American Journal of Physics Education.* 3 [2], 207-213.