FLORE
Repository istituzionale dell'Università degli Studi di Firenze

Experiments on buoyancy and surface tension following Galileo Galilei

Questa è la Versione finale referata (Post print/Accepted manuscript) della seguente pubblicazione:

Original Citation:

Experiments on buoyancy and surface tension following Galileo Galilei / S. Straulino; C.M.C. Gambi; A. Righini. - In: AMERICAN JOURNAL OF PHYSICS. - ISSN 0002-9505. - STAMPA. - 79:(2011), pp. 32-36. [10.1119/1.3492721]

Availability:

This version is available at: 2158/530056 since:

Published version:

DOI: 10.1119/1.3492721

Terms of use:

Open Access

La pubblicazione è resa disponibile sotto le norme e i termini della licenza di deposito, secondo quanto stabilito dalla Policy per l'accesso aperto dell'Università degli Studi di Firenze (https://www.sba.unifi.it/upload/policy-oa-2016-1.pdf)

Publisher copyright claim:

(Article begins on next page)

18 April 2024

Experiments on buoyancy and surface tension following Galileo Galilei

S. Straulino, C. M. C. Gambi, and A. Righini
Dipartimento di Fisica e Astronomia dell'Università di Firenze, Via G. Sansone 1, 50019 Sesto Fiorentino, Italy

(Received 7 December 2009; accepted 2 September 2010)

We analyze passages of Galileo's writings on aspects of floating. Galileo encountered peculiar effects such as the "floating" of light objects made of dense material and the creation of large drops of water that were difficult to explain because they are related to our current understanding of surface tension. Even though Galileo could not understand the phenomenon, his proposed explanations and experiments are interesting from an educational point of view. We replicate the experiment on water and wine that was described by Galileo in his *Two New Sciences*. © *2011 American Association of Physics Teachers.*

[DOI: 10.1119/1.3492721]

I. INTRODUCTION

The statics of fluids was the first scientific love for Galileo, a keen reader of Archimedes' surviving books, guided by the mathematician Ostilio Ricci.[1] Galileo had already discussed Archimedes' principle in his early work, *The Little Balance*.[2] In this paper, we consider aspects of Galileo's writings, whose work is useful for organizing educational demonstrations for students and for analyzing his reasoning.

II. BUOYANCY ACCORDING TO ARISTOTLE AND GALILEO AND ITS RELATION TO SURFACE TENSION

In 1611, Galileo, as the mathematician of the Grand Duke of Tuscany, attended a meeting in the presence of Cosimo II, where the discussion was about the density of ice. Aristotle in his *Physics*[3] affirmed that solid water should have a greater weight than liquid water for the same volume. We know that this statement is incorrect because the density of ice is lower than that of water (hydrogen bonds create an open crystal structure in the solid phase), and for this reason ice can float. Galileo declares that ice has a density lower than water in his booklet *A Discourse Concerning the Natation of Bodies*,[4,5] which was successful and written by request of the Gran Duke. It was published in 1612 as a report of the meeting (quote 1 in the Appendix).

The ideas of the Aristotelian philosophers who attended the meeting sound strange to us today. They believed that ice floats because it is shaped like a plate and it rests above the water's surface. These philosophers could have had in mind the ice slabs that in wintertime are produced on ponds and rivers. They were not experimental physicists and did not test the buoyancy of ice in different shapes, for example, ice cubes. The Aristotelian theory of buoyancy affirms that bodies in a fluid are supported by the resistance of the fluid to being divided by the penetrating object, just as a large piece of wood supports an axe striking it or honey supports a spoon. According to this theory, a boat should sink in shallow water more than in high seas, just as an axe can easily penetrate and even break a small piece of wood, but cannot penetrate a large piece.

The Aristotelian philosophers knew that a small ebony plate or even a thin gold foil, which have densities greater that of water, could float if they are gently laid on the surface of water. Galileo could not explain in a simple way the reason of this phenomenon. He partially solved the issue by considering that the thin plate sinks in water to a small depth such that under the water's surface there is a plate (see Fig. 1), consisting partly of air and partly of ebony or gold. This plate can therefore be considered as a virtual solid, whose specific weight is lower than that of water (quote 2 in the Appendix). It can be observed that around the ebony plate an "embankment" (*rampert* in the 1663 translation) is present (see Fig. 2). For a material with density greater than ebony, the surface of the plate should be more immersed in water, as Galileo remarked, and the immersion should increase if weights are added on the plate as shown in Fig. 2. The solution given by Galileo is incomplete. Today, we know that surface tension plays a role both in preventing water from flowing across the surface of the plate and providing part of the upward force on the immersed body. In contrast, Galileo assumed the existence of a sort of "magnetic attraction" between the air and the light bodies floating on the water (quote 3 in the Appendix). Galileo then claimed that water does not offer resistance when it is separated slowly, but the resistance becomes considerable when water is separated rapidly.

Galileo's explanations did not satisfy the Aristotelian philosophers. Ludovico delle Colombe, a member of the *Accademia Fiorentina* and known in Florence as a mathematician, even wrote a small book against Galileo, who did not personally reply but asked Benedetto Castelli, his former pupil in Padua and Professor of Mathematics in Pisa at that time, to write a short reply reaffirming the Archimedean theory of buoyancy.

III. A PASSAGE ABOUT WATER AND WINE IN THE DISCOURSES ABOUT TWO NEW SCIENCES

Galileo also discussed buoyancy in his book *Discourses about Two New Sciences*,[6] published in 1638. This book is written in dialog form where Salviati represents Galileo, Sagredo is an intelligent and curious character, and Simplicio is the Aristotelian philosopher. Galileo points out that float-

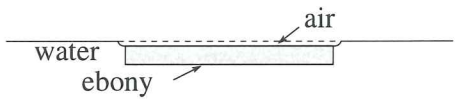


Fig. 1. A thin plate of ebony, if it is gently laid on the surface of water, can float even though this wood has a density greater than water. Galileo considered a "composite plate" made of ebony and air.

 © 2011 American Association of Physics Teachers

Fig. 2. A thin plate of ebony, also bearing some small weights, can float in water, but it sinks when touched.

Fig. 3. A large water drop above a cabbage leaf. The creation of such large drops was not easy to explain for Galileo.

ing can be completely explained by taking into account differences of density between the liquid and the immersed object. Aristotle's theory of floating, based on the "internal coherence" of fluids, was rejected by Galileo. Nevertheless, we now know that the idea of internal coherence of fluids is not completely incorrect because phenomena connected with surface tension, which Galileo could not easily explain, are caused by the mutual attraction of molecules.

After a long discussion leading to rejecting the idea of water's internal coherence, the intelligent Sagredo asks Salviati:

> "There is one great difficulty of which I have not been able to rid myself, namely, if there be no tenacity or coherence between the particles of water how is it possible for those large drops of water to stand out in relief upon cabbage leaves without scattering or spreading out?"[6]

We now know that such large drops (an example can be seen in Fig. 3) can be interpreted as effects of surface tension, but Galileo admits that the origin of them is obscure for him. However, he declared that the reason cannot be the internal coherence of water because the coherence would be greater if water were surrounded by a substance heavier than air such as wine. He then described an apparatus that should demonstrate whether there is internal coherence of water. The apparatus consists of a bottle, filled with water, provided with an open straw inserted in the cork and turned upside down. It can be easily shown that water cannot come out of the bottle. In principle, this coherence of the water should be maintained if the opening of the straw is immersed in the wine, but this is not the case:

> "Having taken a glass globe which had a mouth of about the same diameter as a straw, I filled it with water and turned it mouth downward; nevertheless the water, although quite heavy and prone to descend, and the air, which is very light and disposed to rise through the water, refused, the one to descend and the other to ascend through the opening, but both remained stubborn and defiant. On the other hand, as soon as I apply to this opening a glass of red wine, which is almost inappreciably lighter than water, red streaks are immediately observed to ascend slowly through the water without mixing, until finally the globe is completely filled with wine and the water has all gone down in to the vessel below. What then can we say except that there exists, between water and air, a certain incompatibility which I do not understand, but perhaps..."[6]

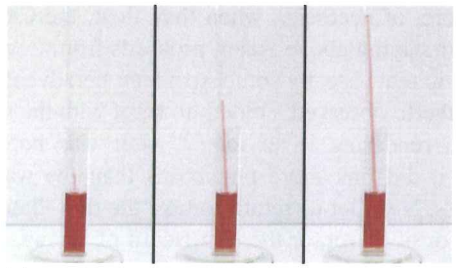
This simple experiment was the occasion for a debate among historians of science, in particular between MacLachlan[7] and Koyré.[8] The latter, who in several cases declared that Galilean experiments have not actually been carried out, in the case of this experiment asserts that "If we repeated [the experiment] *exactly as described*, we should see the wine rise in the glass globe (filled with water), and water fall into the vessel (full of wine); but we should not see the water and the wine simply replacing each other; we should see the formation of a mixture."[8] MacLachlan in 1971 performed the experiment again with simple materials (a drinking straw and a couple of bottles) and was fascinated by the result, which corresponded to the description given by Galileo. After his successful experiment, MacLachlan ended his paper with this sentence: "Probably imaginary this experiment may have been for Koyré, it was certainly a real experiment for Galileo."[7]

According to recent studies by Beltrán,[9] it is possible that a device designed to exchange wine and water was known before Galileo. In the book *Des Monstres et Prodiges*, the French surgeon Ambroise Paré[10] described an instrument, the "wine-raiser," which exhibited an operation very similar to that depicted by Galileo.[11] Given the interest of this simple result from the educational point of view, we propose a simple repetition of the experiment, which is easy to set up in every school's laboratory.

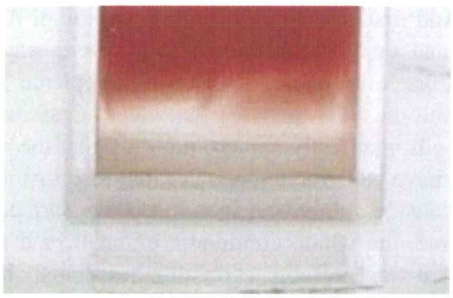
IV. EXPERIMENTS IN OUR LABORATORY

We filled a small glass pipette (2.2 mm inner diameter) with water. The liquid could not come out of the pipette when placed upright and closed at the upper end. Then, we inserted the pipette into a small vessel containing wine.[12]

We observed water descending in wine and wine going up inside water, as described by Galileo[6] and MacLachlan.[7] The process was slow due to the small difference of density between water and wine. In Fig. 4, three consecutive pictures of the process are shown. We observed that water and wine moved into each other without mixing, and while wine was going into the water, water descended into the wine and created a transparent layer on the bottom of the vessel (visible in the enlarged photo of Fig. 4). We found that wine rose in



(a)



(b)

Fig. 4. (a) The red wine goes up inside the pipette at the same time water goes down to the bottom of the vessel: Three consecutive pictures of the process are reported. (b) An enlargement of the third picture shows that water deposits on the bottom of the cell.

the pipette at a speed of about 2 mm/s consistent with the three photos of Fig. 4, which were taken in a few tens of seconds.

Whether the motion of a fluid in a pipe is laminar or turbulent can be determined by calculating the dimensionless Reynolds number R,

$$R = \frac{\rho v d}{\eta}, \tag{1}$$

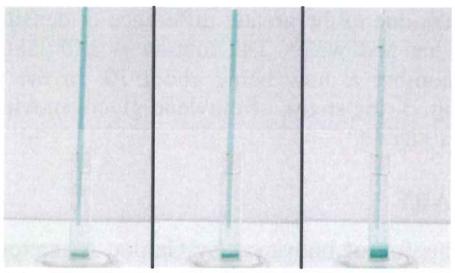
where ρ is the density of the fluid, v its velocity, d the inner diameter of the pipe, and η is the fluid viscosity. Turbulence corresponds to values of R greater than a few thousands. In our case, we can estimate that $R \approx 4$, and observation by the naked eye confirms that the motion inside the pipe is laminar.

If we consider two nonmiscible liquids, for example, water and oil, and pour them together in a container, we observe a stratification where the difference in density causes the oil to settle above the water. The experiment of water and wine is a demonstration that stratification is possible also with miscible liquids but only under laminar flow. The capillary tube plays a fundamental role in the experiment. We have verified that the exchange of the liquids is much slower for a pipette whose inner diameter is 1 mm or less. On the contrary, a wide tube makes wine and water mix with turbulent motion, as happens in a water glass. In contrast, for conditions of laminar flow, diffusion gives rise to a complete mixing of the fluids only on a longer time scale (of the order of 1 day).

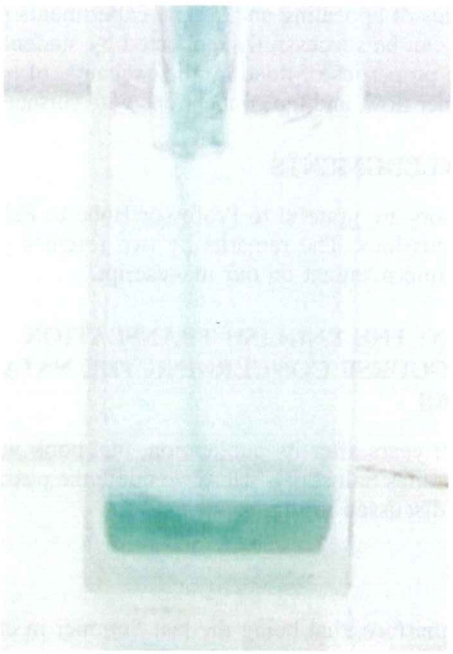
The rise inside a capillary of a liquid such as water in contact with air is related to the static fluid pressure,

$$\Delta P = \rho g h, \tag{2}$$

where ρ is the fluid density, g is the gravitational acceleration, and h is the rise into the capillary. ΔP is the pressure difference due to the curved meniscus, which is described by



(a)



(b)

Fig. 5. (a) The ethylene glycol descending in water. (b) The enlargement of the cell shows a green steak of ethylene glycol inside the water and a stained layer on the bottom of the cell.

Laplace's equation.[13,14] According to Laplace's equation, the difference in pressure between the convex meniscus (air) and the concave liquid is

$$\Delta P = \frac{2\gamma}{R}, \tag{3}$$

where γ is the surface tension and R is the radius of the convex curve (R is related to the capillary radius r by $r = R \cos \theta$, where θ is the contact angle of the liquid on the vertical surface of the tube).

According to Eq. (3), the difference in pressure ΔP is created by the presence of surface tension, and because of this pressure, the liquid does not flow from the vertical pipette into the air. When the pipette is inserted into the wine, the pressure ΔP goes to zero and the exchange between the two liquids takes place on a time scale governed by the dimensions of the tube.

We also used ethylene glycol, a liquid more dense than water, which is commonly used as an automobile antifreeze and has a density of 1.11 g/cm^3. We repeated the previous test with water in the vessel and the ethylene glycol in the pipette. We observed that the ethylene glycol descended into water (Fig. 5) and created a stained layer on the bottom of the vessel. In this case, the speed of the moving liquid was

about 5 mm/s due to the greater difference of densities compared to wine and water. The motion is still laminar, the Reynolds number R now being about 10. In the enlarged photo of Fig. 5, the streak of ethylene glycol moving inside the water is visible.

V. SUMMARY

The discussion of buoyancy by Galileo is interesting because it marks the passage from Aristotelian physics to the reasoning of modern science. From the educational point of view, a series of appealing and simple experiments proposed by Galileo can be successfully replicated by students to emphasize the properties of floating, the exchange of two fluids under laminar flow, and the connections with surface tension.

ACKNOWLEDGMENTS

The authors are grateful to Professor Roberto Falciani for fruitful discussions. The remarks by two referees yielded a significant improvement on our manuscript.

APPENDIX: THE ENGLISH TRANSLATION OF A DISCOURSE CONCERNING THE NATATION OF BODIES

About 50 years after its publication, this book was translated by Thomas Salusbury.[4] Here we quote the passages that have been discussed in this paper.

1. Quote 1

> I say therfore, that being the last Summer in company with certain Learned men, it was said in the argumentation; That Condensation was the propriety of Cold, and there was alledged for instance, the example of Ice: now I at that time said, that, in my judgment, the Ice should be rather Water rarified than condensed, and my reason was, because Condensation begets diminution of Mass,[15] and augmentation of gravity,[16] and Rarifaction causeth greater Lightness,[17] and augmentation of Masse: and Water in freezing, encreaseth in Masse, and the Ice made thereby is lighter than the Water on which it swimmeth. [...] I say then the Cause why some Sollid Bodyes descend to the Bottom of Water, is the excesse of their Gravity, above the Gravity of the Water; and on the contrary, the excess of the Waters Gravity above the Gravity of those, is the Cause that others do not descend, rather that they rise from the Bottom, and ascend to the Surface. This was subtilly demonstrated by Archimedes in his Book Of the Natation of Bodies.[18]

2. Quote 2

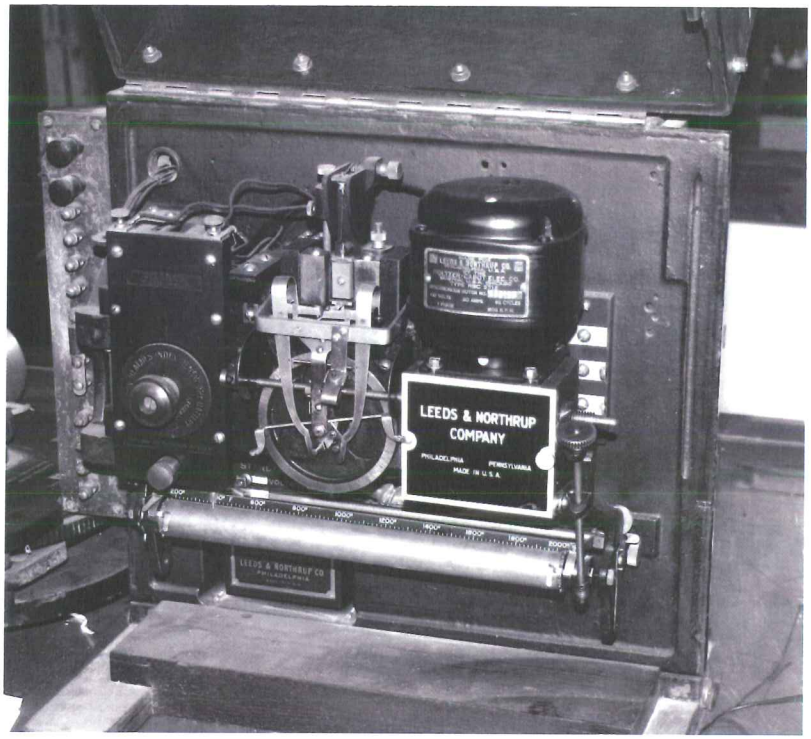
> And because, that the excess of their Gravity above the Gravity of the water, is questionless the Cause of the sinking of the flat piece of Ebony, and the thin Plate of Gold, when they go to the Bottom, therefore, of necessity, when they float, the Cause of their staying above water, proceeds from Levity, which in that case, by some Accident, peradventure not hitherto observed, cometh to meet with the said Board, rendering it no longer as it was before, while it did fink more ponderous than the water, but less. Now, let us return to take the thin Plate of Gold, or of Silver, or the thin Board of Ebony, and let us lay it lightly upon the water, so that it stay there without sinking, and diligently observe its effect. And first, see how false the assertion of Aristotle, and our oponents is, to wit, that it stayeth above water, through its unability to pierce and penetrate the Resistance of the waters Crassitude: for it will manifestly appear, not only that the said Plates have penetrated the water, but also that they are a considerable matter lower than the Surface of the same, the which continueth eminent, and maketh as it were a Rampert on all sides, round about the said Plates, the profundity of which they stay swimming: and, according as the said Plates shall be more grave than the water, two, four, ten or twenty times, it is necessary, that their Superficies do stay below the universall Surface of the water, so much more, than the thickness of those Plates, as we shal more distinctly shew anon. [...] Which in this case descends and is placed in the water, is not only the Board of Ebony or Plate of Iron, but a composition of Ebony and Air, from which resulteth a Solid no longer superiour in Gravity to the water, as was the simple Ebony, or the simple Gold. And, if we exactly consider, what, and how great the Solid is, that in this Experiment enters into the water, and contrasts with the Gravity of the same, it will be found to be all that which we find to be beneath the Surface of the water, the which is an aggregate and Compound of a Board of Ebony, and of almost the like quantity of Air, or a Mass compounded of a Plate of Lead, and ten or twelve times as much Air.[19]

3. Quote 3

> I affirm, that the contiguous superiour Air is able to sustain that Plate of Brass or of Silver, that stayeth above water; as if I would in a certain sence allow the Air, a kind of Magnetick vertue of sustaining the grave Bodies, with which it is contiguous. To satissie all I may, to all doubts, I have been considering how by some other sensible Experiment I might demonstrate, how truly that little contiguous and superiour Air sustaines those Solids, which being by nature apt to descend to the Bottom, being placed lightly on the water submerge not, unless they be first thorowly bathed.[20]

[1] Alberto Righini, *Galileo tra Scienza, Fede e Politica* (Compositori, Bologna, 2008).

[2] Galileo Galilei, *The Little Balance*, written in 1586 and published in 1644 after the author's death.
[3] Aristotle, *Physics*, translated by Robin Waterfield, edited by David Bostock (Oxford U. P., Oxford, 1999).
[4] Galileo Galilei, *A Discourse Concerning the Natation of Bodies* (1612), translated into English by Thomas Salusbury, 1663 (U. of Illinois Press, Urbana, IL, 1960). Available at ⟨en.wikisource.org⟩.
[5] S. Drake, *Cause, Experiment and Science: A Galilean Dialogue Incorporating a New English Translation of Galileo's "Bodies That Stay atop Water or Move It"* (U. of Chicago Press, Chicago, 1981).
[6] Galileo Galilei, *Dialogues Concerning Two New Sciences* (1638), translated from the Italian and Latin into English by Henry Crew and Alfonso de Salvio (Macmillan, New York, 1914) See: ⟨en.wikisource.org⟩.
[7] J. MacLachlan, "A test of an 'imaginary' experiment of Galileo's," Isis **64** (3), 374–379 (1973).
[8] A. Koyré, *Metaphysics and Measurement. Essays in Scientific Revolution* (Harvard U. P., Cambridge, 1968).
[9] A. Beltrán, "Wine, water, and epistemological sobriety: A note on the Koyré–MacLachlan debate," Isis **89** (1), 82–89 (1998).
[10] A. Paré, *Des Monstres et Prodiges*, translated into English by Janis L. Pallister as On Monsters and Marvels (U. of Chicago Press, Chicago, 1982).
[11] "... [this] is shown to us by the experiment of two glass vessels—called montevins—the upper one of which being filled with water and the lower with wine, when placed one on top of the other, one manifestly sees the wine mount to the top across the water and the water descend across the wine, without their becoming mixed together..." (Ref. 10).
[12] The density of the wine was measured by a Mohr–Westphal's balance at 24 °C and yielded 0.991 ± 0.001 g/cm^3. It is "almost inappreciably lighter than water," as Galileo says, because water's density is 0.997 g/cm^3 at the same temperature.
[13] H. N. V. Temperley and D. H. Trevena, *Liquids and Their Properties; A Molecular and Macroscopic Treatise with Applications* (Ellis Horwood, Chichester, 1978).
[14] D. H. Everett, *Basic Principles of Colloid Science* (Royal Society of Chemistry, London, 1988).
[15] In the original text, *Mass or Masse* is "mole," which in Italian stands for "bulk," or "volume" in modern physics parlance.
[16] *Augmentation of gravity* is equivalent to "increase of the specific weight." Also, in the following, the word gravity stands for specific weight.
[17] *Greater Lightness* is equivalent to "decrease of the specific weight."
[18] Reference 4, pp. 3–5.
[19] Reference 4, pp. 34–36.
[20] Reference 4, pp. 38–39.



Temperature Recorder. In a 1912 catalogue, Leeds & Northrup of Philadelphia described their line of strip-chart recorders to be used with probes that either changed their EMF or their resistance with temperature. The heart of the system was the circular slide wire in the middle of the instrument. For resistance-sensitive probes this was part of a Wheatstone bridge circuit that was constantly being rebalanced as the temperature changed. The slide wire then drove the pen back and forth across the paper that was held by the roller across the bottom. This instrument is in the Niagara Science Museum in Niagara Falls, NY, and cost $200 to $250. (Notes and photograph by Thomas B. Greenslade, Jr., Kenyon College)