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SOLUTION TO THE LONG STANDING PUZZLE OF HUYGENS' "ANOMALOUS SUSPENSION"

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Abstract. In 1662 Christiaan Huygens carried out the famous Torricelli experiment to test the existence of atmospheric pressure by inserting the apparatus in the glass receiver of a vacuum pump, and evacuating the air inside it. He reported that when the air was exhausted, a column of water remained suspended in a 4 foot tube. This unexpected result was in stark contrast with earlier experiments of Boyle and Hooke that apparently had confirmed Torricelli's explanation that such a water column was supported by outside air pressure, and would fall when the air was removed. Huygen's "anomalous suspension" led to the continuation of controversies in the 17th-century about the nature of the *vacuum* that these experiments were expected to resolve. Surprisingly, the origin of Huygens' unexpected result has remained a puzzle up to the present time.

In this paper, I discuss the dynamics of such a column of water under the different experimental conditions reported by Boyle and by Huygens, that turned out to be different, and present the results of a replication of their experiments with a modern vacuum pump. Contrary to the conventional explanations of these experiments, I demonstrate that in the Boyle-Hooke version of this experiment, the water column descends initially because it is forced down by the gas pressure due to air dissolved in the water which is released inside the Torricelli tube after the external pressure is sufficiently decreased. Huygens', however, first removed this trapped air before he carried out his experiment. In the absence of this internal gas pressure, the early rudimentary vacuum pumps were inadequate to decrease the air pressure sufficiently inside the receiver to demonstrate the descent of a Torricelli column of *airless* water 4 foot in height or less.

Introduction

In 1660 Robert Boyle published a report of a series of experiments [1] which he undertook with the assistance of Robert Hooke, to study the physical properties of air. For this purpose Hooke, with the help of a technician, designed and constructed a vacuum or air pump after seeing a report of Otto von Guericke's invention of such a pump. In the opening remarks of his report, Boyle explained the motivation for these experiments

> ...perceiving by Letters from some other Ingenious Persons at *Paris*, that several of the *Virtuosi* there, were very intent upon the examination of the Interest of the Ayr, in hindring the descent of the Quick-siver [mercury], in the famous experiment touching on the *Vacuum* ... by prosecuting and endeavoring to promote the noble experiment of *Torricellius*...[2]

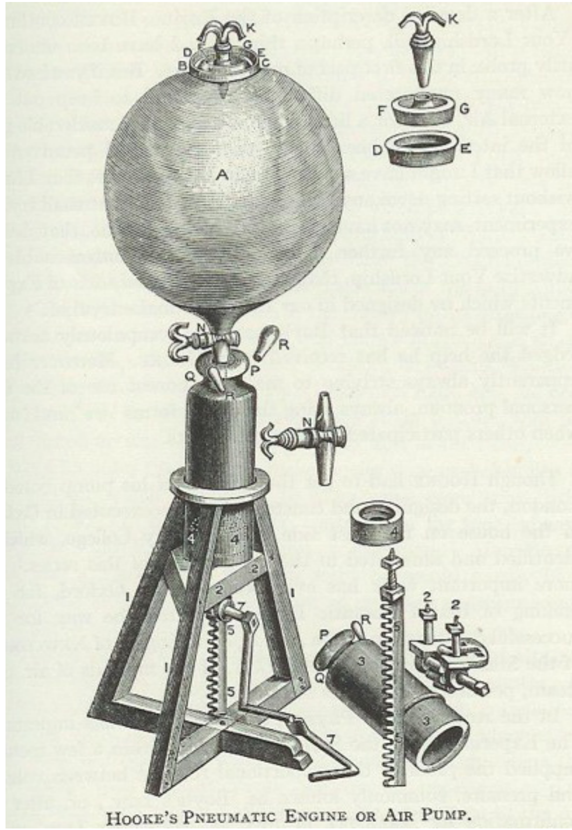

FIGURE 1. Hooke's airpump with a spherical glass receiver placed on top of it.

Actually, Evangelista Torricelli's famous experiment was first carried out by a former student of Galileo, Vincenzio Viviani [3], by filling with mercury a long glass tube closed at one end, placing a finger on the open end, and then inverting the tube in a container with some mercury. On removing the finger some of the mercury is released from the tube leaving a column of mercury 76 cm. in height standing inside the tube. At the time, there was considerable disagreement about the explanation for this phenomenon. Torricelli argued that the weight of the column of mercury was supported by the pressure of the surrounding air, and he maintained that the space left between the top of the column and the top of the tube, was a *vacuum*. The plenists, however, following Aristotle's ideas, believed in his dictum that nature *abhors a vacuum*, and claimed that the apparently empty space above the top of the column contained a "subtle fluid" that somehow suspended the mercury column inside the tube. The experiments of Boyle and Hooke were intended to shed light on this question by enclosing the Torricellian apparatus inside a closed glass jar or receiver, and exhausting the air in this receiver with an air pump. If the mercury column fell as the air was evacuated, the argument of Torricelli and his followers would be supported by an *experimental test*, a novel and controversial concept at the time [4]; otherwise the claim of the plenists for suspension of this column by a subtle fluid would be supported. For example, the well known philosopher Thomas Hobbes declared that :

> Whoever sucks water into his mouth through a tube first sucks the air in between... which being removed cannot have a place (in a plenum) except by moving that next to it: and so by continual pressure the water is driven into the tube, and replaces the air that is sucked out [31].

Boyle reported [1] that both a mercury and a water column in a Torricelli setup placed inside the receiver of their air pump, Fig.1, descended as the air was evacuated with their pump, claiming that this result supported Torricelli's explanation. But soon afterwards, Christiaan Huygens announced that he had repeated this experiment inside a receiver of an air pump of his own design, Figs.2, 3, but he found that after first removing the air bubbles in the water which had appeared when he first activated his pump, that the Torricellian column of water in his receiver failed to descend no matter how long his pump was in operation [6]. Huygens' unexpected phenomenon was called "anomalous suspension",

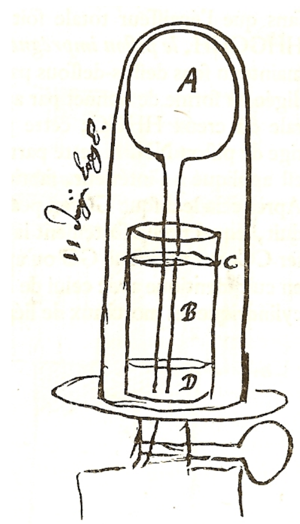

FIGURE 2. Huygens' apparatus for a Torricelli experiment placed inside the receiver of his air pump, ref. [6] p.317

and it was claimed by him and other plenist that this experiment supported the existence of a "subtle fluid" in the space above the water column that suspended it. For a long time his experiment with *airless* water could not be replicated, but eventually Hooke and others confirmed his result, although apparently neither Boyle nor Hooke accepted Huygens' explanation for it [7].

Remarkably, the origin of anomalous suspension was not clarified, and it has remained an unsolved puzzle to the present day. In *Huygens' and the development of the air pump*,

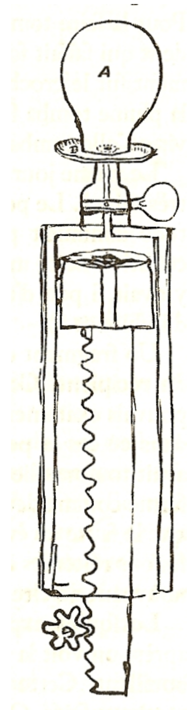

FIGURE 3. Huygens' original air pump. The receiver A is on top and the air pump with its piston is below. When the piston descends, the valve below the receiver is opened to allow the air in the receiver to expand into the cavity of the pump. When the piston ascends this valve is closed, and a second valve attached to the pump, but not shown in this diagram, is then opened to exhaust the air in the pump, ref [6] p. 313

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Alice Stroud wrote that "no one had been able to explain it [anomalous suspension]" [8], while in *The age of the air pump*, Anne C. Van Helden wrote that "today the phenomenon is attributed to adhesion between the water and he glass tube" [9]. More recently in his biography of Huygens, Rienk Vermij repeated this claim, apparently first made by Schaffer and Shapin in their book, *Leviathan and the Air Pump* [7], that "this puzzling phenomenon is caused by the adhesion force between H_2O molecules and the glass of the air pump" [10]. It will be shown, however, that this explanation is not valid, and that Boyle's report of his experiment reveals that he and Hooke already had some understanding for the origin of the so-called anomalous suspension reported by Huygens.

This paper is organized as follows: Section I describes some of the historical background which led to Torricelli's experiment, Section II gives a qualitative explanation for the dynamics of a Torricellian water column under the *different* experimental conditions of Boyle-Hooke and of Huygens, Section III describes the result of an experiment that replicates the Boyle-Hooke and Huygens experiments with a modern vacuum pump, and Section IV provides some concluding remarks.

I Historical background

The construction of the vacuum pump and the discovery of the physical properties of air was, undoubtedly, the most important development in experimental science at the beginning of the scientific revolution [11]. In his book, "Dialogues Concerning Two New Sciences", Galileo reported a fact already commonly known at the time, that water from a cistern could not be lifted with a suction pump higher than eighteen cubits [12] [13]. He explained this limit by an analogy: to lift a " rope, or rod of wood, or of iron, which if sufficiently long would break by its own weight when held by the upper end..."[13]. What held the upper end of a column of water he attributed to the vacuum created by a suction pump. Aristotle had taught that " nature abhors a vacuum", and his followers, the plenists, believed that some sort of "subtle fluid" occupied the region above the water where air had been exhausted by the pump, which somehow suspended the water column. There are several accounts that around 1642-43, Gasparo Berti devised an ingenious experiment, to determine the maximum height of this water column [14]. Instead of pumping air out, he filled with water a long tube clamped by ropes to the side of his house, which could be opened or closed at both ends by "threaded brass screws" taps. The lower end of this tube was immersed in a casket filled with water, and the valve at this end was opened, while the valve at the top was closed, see Fig.4. Berti found that the water in the column then dropped until it reached a height of "eighteen cubits above the level of the water in the cask", a result in agreement with the limit reported by Galileo. Berti also claimed to confirm that the space left in the tube above the column of water did not contain air, because when he closed the bottom valve and opened the top valve air rushed in "with a great noise" [14].

According to a later account by Carlo Dati, a disciple of Torricelli who had known Galileo, Vincenzio Viviani, carried out a similar experiment at the request of Torricelli, but using mercury instead of water. Galileo had pointed out that, according to his theory, the maximum possible height of a *suspended* column of fluid would be inversely proportional to its density. Hence, by using mercury, Viviani could use a much shorter tube and dispense with the valves in Berti's experiment. In a letter written on June 11, 1644 to his friend Cardinal Michelangelo Ricci [15], Torricelli reported that the maximum height of the column of mercury was an "ell and a quarter and a finger more"[16] [17]. Contrary to Galileo, however, Torricelli reasoned correctly that the column of mercury was held up by the pressure of the surrounding atmospheric air. This explanation also had been proposed, independently, by Isaac Beeckman in Holland, but it was not accepted by the plenist. In addition, a controversy had ensued about the nature of the space above the water column supposedly evacuated of air. The observation that light, magnetism, and apparently sound was transmitted in this space was given as evidence of the presence of a subtle fluid which the plenist claimed was responsible for the suspension of the fluid column. But new evidence that the surrounding air supports the mercury column was obtained by Blaise Pascal

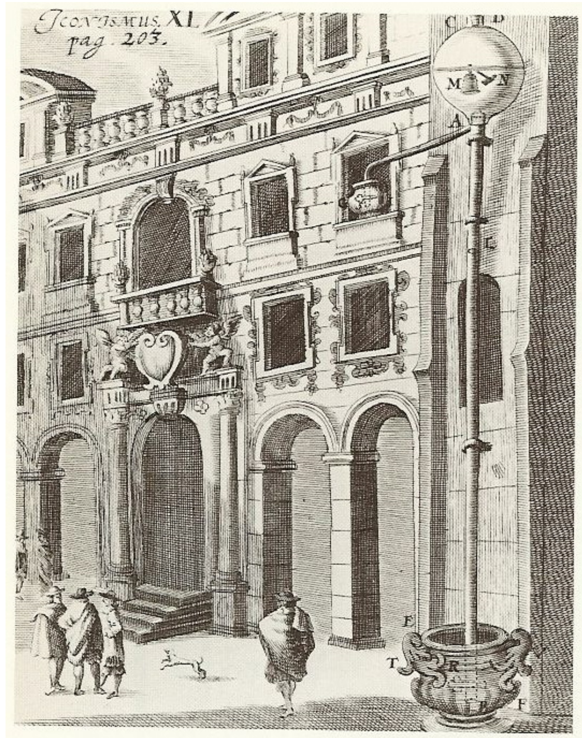

FIGURE 4. Gasparo Berti's experiment

who had urged his brother-in-law, Perier, to take such a mercury *barometer* (as it is called now) up a mountain, the Puy-de- Dôme, in order to check whether at higher altitudes, where air pressure supposedly decreases, the mercury column falls somewhat. On Sept. 19, 1648, he found that at the top of the mountain the height of the mercury column was "three inches and one-and-a- half lines " less than at the foot of the mountain. In addition, Adrien Auzout and Roberval carried out a "vacuum within a vacuum" experiment which removed the air surrounding their barometer tube, causing the mercury column to disappear [18] .

In his book [1], Boyle reported 46 experiments with his air pump, and in experiment #19, he described the behavior of a Torricellian column of water inserted in the receiver when the air was evacuated:

> We took then a Tube of Glass, Hermetically seal'd at one end, of about four foot in length, and not very slender: This at the open end we fill'd with common Water, and then stopt that end till we had inverted the Tube, and open'd it beneath the surface of a quantity of the like Water, contain'd in a somewhat deep and slender Vessel. This Vessel, with the Tube in it was let down into the Receiver, and the Receiver being clos'd up after the accostum'd manner, the pump was set awork . . . That till a considerable

> part of the Air was drawn out of the Receiver, the Tube continu'd top-full of Water as when it was put in, it being requisite that a great part of the Air formerly contain'd in the Receiver, should be drawn out, to bring the remaining Air to an *AEquilibrium* with so short and light a Cylinder of Water.
>
> But when once the Water began to fall in the Tube, then each exsuction of Air made it descent a little lower, tought nothing near so much as the Quick-silver [mercury] at the beginning did in the Experiment formerly mention'd. Nor did there appear so much inequality in the spaces transmitted by the Water in its descent, as there did in those observ'd in the fall of the Quick-silver ... And whereas we drew down the Quick-silver in the Tube so far as to bring it within and inch of the surface of the other Quick-silver into which it was to fall, the lower we were able to draw down the water was, by our conjecture, to about a Foot or more above the surface of the Vessel; of which I know not whether if will be needful to assign so obvious a cause as that , though the little Air remaining in the Receiver could not hinder a Cylinder of above an Inch high of Quick-silver from subsiding; yet it might very well be able by its pressure , to countervail the weight of a Cylinder a Foot long or more, of Liquor so much less ponderous than Quick-silver, as Water is [19].

This experiment caused considerable excitement among the 17-century *virtuosi* interested in the new method of scientific experimentation, and it appeared that the *vacuist*, who accepted Torricelli's explanation, had won the day. Unfortunately, the experiment could not be replicated easily, because building an air pump was a very difficult enterprise. In Holland, Christiaan Huygens heard reports about these observations, and since he had been very interested in the Torricelli experiments in Italy and France because of its significance for the existence of a vacuum, he visited Boyle in London to learn about his work. Soon after his return, he began to construct a similar but improved (by his account) air pump to replicate these experiment himself [6]. After overcoming some considerable difficulties, he succeed in building such a pump, Figs.2,3, and at the beginning, he found results similar to those obtained by Boyle and Hooke, reporting that "after five or six strokes of the pump" the water in the Toricellian column fell to the level of the water in the basin [20]. But while activating his air pump, Huygens had observed that there was a considerable formation of bubbles in the water which he attributed to air dissolved in water. This important bubble formation, which generally has been overlooked in modern accounts of this experiment, had been reported also earlier by Boyle in his experiment # 22 :

> We shall now adde, that in the like Experiment made in such a Tube, or a greater, it may be observ'd, That when the Water begins to fall there will appear store of bubbles fasten'd all along the sides of the Glass; of which bubbles, by the agitation of the Vessel consequent upon the pumping, there will arise a good numbers to the top of the Water, and there break; and

> as the Cylinder of Water is brought to be lower and lower, so the bubbles will appear more numerous in that part of the Tube which the Water yet fills...[21]

The reason why the water column did not descend until "a great part of the Air" in the receiver had been exhausted, was that initially the dissolved air in the water appearing as bubbles, adhered to the walls of the glass tube. Therefore, early on it did do not contribute to the internal gas pressure which later pressed downwards on the water column.

In a subsequent experiment, Huygens operated this vacuum pump for a sufficient long time until bubbles ceased to emerge from the water, and then he repeated the experiment with his airless water. This time, to his surprise, after exhausting as much air as he could from his receiver, the column of water did not fall. This unexpected outcome, which became known as "anomalous suspension", appeared to support the claims of the plenist who denied the existence of a vacuum. But initially Hooke and other members of the Royal Society where unable to replicate it, and questioned its existence. Eventually, however, with the help of Huygens, who travelled to London to demonstrate anomalous suspension, Hooke and others were able to reproduce it. But Hooke and Boyle remained unconvinced by Huygens' interpretation of his experiment with water purged of air, and the controversy between plenist and vacuuist remained unresolved [8], [7],[10].

II Origin of "anomalous suspension"

During the 17-th century the origin of anomalous suspension was controversial, but surprisingly, it has remained a puzzle up to the present time. A clue to this puzzle is the observation that before this so-called anomaly could be observed, it was necessary to remove the dissolved air normally contained in water open to the atmosphere. That air or some other gas is present in water already had become evident to Boyle and Hooke, because during the early phase of air evacuation from the receiver they had observed that bubbles form inside the glass walls containing the water column. These bubble first attach themselves to impurities on the glass, but as the pressure of the air inside the receiver decreases, these bubbles become detached from the glass walls and ascend to the top of the water column, giving rise to gas pressure *inside* the Torricellian tube. It will be shown that it is this pressure, in addition to the weight of the water column, that initially forces the water column down. Hence, the conventional explanation, that the water column *starts* to fall when its weight can no longer be supported by the pressure of air remaining in the receiver, is incorrect. Remarkably, Boyle and Hooke already had provided evidence that trapped gas gave rise to additional downward pressure on the water column, observing that by heating it, it "quickly drave the Water to the bottom of the Tube . . ." In experiment #22 of his report, Boyle revealed,

> That upon the inletting of the external Air, the Water was not again impell'd to the very top of the Tube whence it began to fall, but it was stop in its ascent near an Inch beneath the top ... The Phoenomenon under consideration seem'd manifestly to argue that the many bubbles that broke at the top of the Water did contain a real Air, which, being collected into

> one place and hindered by the top of the Glass from receding, was able to withstand the pressure of the outward Air... We drew the second time the Air out of the Receiver and found that by reason of the body that possess'd the top of the Tube, we were able not only to make the Water in the Tube fall to a level with the surface of the Water in the Vessel: But also (by plying the Pump a little longer) a great way beneath it: which since it could not well be ascrib'd to the bare subsiding of the Water by reason of its weight, argued that the Water was depress'd by the Air: which was confirm'd by the Figure of the surface of the Water in the Tube, which was much more concave then that of Water in Tubes of that bigness uses to be. And this further tryal (to adde that upon the by) we made at the same time, That when the Water in the Pipe was drawn down almost as low as the Water without it, we observ'd, that (though we desisted from pumping) by the bare application of hand moderately warm to the deserted part of the Tube, the remaining Water would be speedily and notably depress'd. And having for a while held a kindle Coal to the outside of the Tube(the Pump being still unimploy'd, because the Vessel chance to hold extraordinarily well) the Air was by the heat so far expanded, that quickly drave the Water to the bottom of the Tube, which was divers Inches beneath the surface of the ambient Water...[21]

Although Huygens also had noticed the presence of these air bubbles, he decided to remove them by first placing the water in a container inside the receiver, and activating his air pump until the air bubbles that initially formed had disappeared. Afterwards, he conducted the Torricellian experiment with this airless water. In a June 1662 letter to J. Chapelain and R. Moray, he wrote:

> To carry out the same experiment with the air removed from the water, I left, for an entire night, the receiver exhausted from air after I made the water from the tube descend in the manner described. And the next day the water in the basin did not emit a single bubble of air... I continue to activitate the pump to a vacuum .., but the water in the tube did not descent at all, but remained suspended. [22]

Hence, a plausible explanation why the column of airless water in Huygens' experiment did not fall even after extensive pumping, was that enough air remained in the receiver to support the weight of his four foot water column. Later, when Hooke finally was able to replicate Huygens result, he added perceptively that "I am very confident that if the pump had been longer plied, the event would have been much otherwise" [24]. But other practitioners apparently failed to understand that the rudimentary early air pumps did not removed sufficient air from the receiver for a a four foot column of airless water to fall [23]. Moreover, during the ensuing disputes, no one seemed to have heeded Boyle's injunction that a gauge was needed to determine the air pressure of the residual air inside the receiver. Boyle conceded that the new experiments in London by Huygens and by Lord Brouncker to verify anomalous suspension " was try'd ...wth very good successe" [24], but he argued that

> in regard they had noe Gage to try how farre they had exhausted ye Aire in the Receiver it seem's not absurd to conjecture that there might remaine in ye Receiver enough [air] to keep up in ye Tube 3 or 4 foot of Water [24].

To support the weight of a 4 foot column of airless water, including the effect of water vapor, requires a residual air pressure greater than .15 of atmospheric pressure which evidently must have been the limit reached by the early rudimentary vacuum pumps. Eventually, it was observed that such a water column would fall, either because some dissolved air had remained in the water and was slowly released inside the tube, or because air slowly leaked into the receiver [25]

III Replication of the Boyle-Hooke and the Huygens air pump experiments

I replicated the Boyle-Hooke and the Huygens air pump experiments with a short Torricellian column, and a modern vacuum pump, shown in Fig.5.

Figure 5. Torricelli setup inside the receiver (glass jar) of a vacuum pump, consisting of a beaker nearly full of water, and an initial column of water in an inverted glass tube held in position by tape. The vacuum pump with a pressure gauge is seen in the background.

The glass tube in my experiment was 23.7 cm in length, and I filled it with ordinary tap water inverting the open end of the tube into a beaker partially filled with water. The resulting water column was 14.5 cm above the water surface in the beaker. The pressure due to such a column of water corresponds to 10.7 mm. of mercury. When I started to evacuate the air from the receiver, I found that gas bubbles began to form, as Boyle and Huygens had reported, which initially remained attached to the glass wall of the beaker and the tube. As the pumping continued, however, these bubbles began to detach from the glass wall and at the same time the water column began to fall although the pressure inside the receiver was still well over 100 mm. of mercury, i.e. more than 10 times the pressure due to the weight of my initial water column. Evidently, the water column began to fall because the pressure of the gas formed by the bubbles surfacing inside the tube exceeded the pressure of the air still remaining inside the receiver. When the top of the water column reached the level of the water in the beaker, I recorded a pressure over 30 mm of mercury corresponding to the gas pressure inside the tube. This pressure is in part due to water vapor pressure, which is 24 mm of mercury at $T = 25^0 C$, but it drops rapidly with decreasing temperature, while the excess pressure is due to the air from the bubbles released inside the tube. At the rate of pumping in my experiment, however, the water cooled considerably below room temperature, and a better estimate of the residual vapor pressure would be 5-10 mm of mercury. Further pumping depressed the top of the water column further inside the tube below the water level in the beaker. When the pressure in the receiver reached about 10 mm of mercury the column of water inside the tube essentially vanished while a large bubble of gas was released a the bottom of the tube. Some water then re-entered the tube while the surface of the water in the beaker began to boil violently. I waited until the boiling began to subside and then allowed the air to re-enter into the receiver forming again a water column in the tube. Now, like Huygens, I had water that had been purged at least partially of dissolved air. I let air return to the receiver, and when I began pumping air out of the receiver, the water column did not start to fall until the pressure was considerable lower than before. If the gases confined in the water had been removed entirely, I would have expected that the critical pressure below which the water column begins to fall would be 24+10.7= 34.7 mm of mercury, but I found that some gas still remained inside the tube because the column started to fall at a higher pressure of about 50 mm. of mercury.

My experiment revealed some complications not taken into account by the simplified discussion in the previous section. I assumed that during the exhaustion of air in the receiver by the vacuum pump activated at a finite rate, the partial pressure of each component of the air dissolved in the water is in equilibrium with the corresponding component in the external air. However, this is not the case for at least two reasons: 1) it takes some time for this equilibrium to be established, and therefore complete equilibrium does not occur when the exhaustion of air from the receiver is changing continuously, and 2) there is clear evidence that as the external air pressure is decreased, some of the gas dissolved in the water first form bubbles which do not emerge right away, but instead become attached to the glass wall of the Torricellian tube, as was originally reported by Boyle and Hooke and by Huygens. The net effect is that for any given external pressure, initially there is less gas than expected inside this tube, and therefore the height of the water in the tube for a given external pressure was higher than expected.

Direct evidence for the gas released inside the Torricellean tube was obtained by continuing to exhaust air from the receiver until the water column fell to the bottom of the beaker. At this point a very large bubble emerged violently from the bottom of the tube, demonstrating unequivocally the existence of this gas. After returning the air into the receiver, I found as expected that the column of water, now purged of some dissolved air, starts to fall when the air pressure in the receiver is considerable lower than earlier, in the case of normal (tap) water. Moreover, in the case of airless water the pressure at which the top of the column reaches the level of the surrounding water in the beaker corresponds closer to the pressure of water vapor, while it is considerable higher in the case of normal water.

For a further experimental demonstration, I inserted two identical Torricelli devices under the same receiver, but one contained tap water while the other had water previously boiled to release some of the dissolved air. After the vacuum pump was turned on and the air pressure inside the receiver decreased sufficiently, the device containing the tap water began to release air bubbles and the column of water dropped, while the corresponding column in the device with airless water remained in place. A video recording of this experiment can be seen at reference [26].

IV Concluding remarks. I have shown experimentally that the descent of a Torricellian column of water as a function of external air pressure is quite different for ordinary (tap) water, corresponding to the experiment of Boyle and Hooke, than for *airless* water, corresponding to the experiment of Huygens. I have shown that the reason why the early Boyle-Hooke experiments confirmed Torricelli's "elastic power in the air", was that air originally dissolved in water, was released from the column of water inside their tube during pumping, providing downward pressure on this column. This effect had not been anticipated, and it was ignored during the controversies about the existence of Huygens anomalous suspension, that occurred because Huygens had removed the dissolved air in the water, before carrying out his experiment. From my replication of these experiments described in Section III, I conclude that the early air pumps were not adequate to lower the external pressure sufficiently to depress a 4 foot column of *airless* water in a Torricelli tube like Huygens', thus given the appearance of an anomalous suspension of water in his tube.

The description in Experiment #22 by Boyle and Hooke, indicates that they had found that some dissolved air was released from the water column when the external air pressure was decreased by their air pump. Moreover, they also had observed by heating this gas, that it would expand exerting an additional pressure on top of this column, but the significance of their observations apparently escaped Huygens' attention. This is particularly surprising, because Huygens understood very well the linear relation between pressure and density of air (at constant temperature) which had been established experimentally by Boyle and Hooke [27, 28]. Indeed, soon after learning about their experiment, Huygens applied this relation, now known as Boyle's law, to obtain a relation between pressure and height in the atmosphere [29].

Modern historians of science have come up with various unphysical explanations for the non-existent phenomenon of anomalous suspension. For example, in a a short footnote to the extensive discussion of the Boyle-Hooke vs. Huygens controversy in their book

Leviathan and the Air Pump, Shapin and Schaeffer proposed that "some of the factors which could be considered relevant to a current scientific explanation of anomalous suspension [are]: (1) Short range attractive forces between fluid and glass; (2) viscosity; (3) surface tension: (4) the presence of residual air [in the receiver] " [30]. It turns out, however, that only (4) was a correct guess, but by itself it does not explain why Boyle and Hooke did not observed anomalous suspension too. There is no evidence that removing the gases trapped in water would enhance either its viscosity, surface tension or attractive forces to such an extend as to suspend a four foot column of water in a glass tube. Yet up to the present time, similar notions have persisted among other historians of science who have discussed this subject [8],[10]. In the early air pump experiments there must always have been some residual air left in the receiver, but as we have shown here, by itself this residual air does not explain the difference between the initial results reported by Boyle-Hooke in London and by Huygens in Holland.

In their celebrated book, *Leviathan an the Air Pump*, Shapin and Schaeffer conclude that "As we come to recognize the conventional and artifactual status of our form of knowing, we put ourselves in a position to realize that it is ourselves and not *reality* [the italics are mine] that is responsible for what we know . . . Hobbes was right [31]. But this conclusion is based on the false assumption, as Hobbes had asserted, that experiments can not determine the nature of reality. The resulting controversy that began 350 years ago, at the dawn of experimental science, and continues to the present time, is based on the premise that Boyle-Hooke and Huygens were doing experiments under identically the same conditions. But it has been shown here that this premise is false, which accounts for their different experimental outcomes.

Acknowledgements

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[3] W.E. Knowles Middleton *The History of the Barometer*
(Johns Hopkins Press, Baltimore 1964) pp.19-32,37.

[4] For example, Thomas Hobbes declared " Why such apparatus and the expense of machines [such as an air pump] of difficult manufacture, just so you could get as far as Hobbes has already progressed? Why did you not begin from where he left off? Why did you not use the principles that he established?" T. Hobbes, *Dialogus physicus* 1661. Translated and reprinted in S. Schaffer and S. Shapin, *Leviathan and the Air Pump* (Princeton Univ. Press 1985) p. 379.
[5] Ref. [4] p. 381.
[6] "Ouevres Complétes de Christiaan Huygens", Vol. XVII (La Haye, Martinus Nijhoff, 1932)pp. 305 -333.
[7] S. Shapin and S. Schaeffer, Leviathan and the Air Pump (Princeton University Press 1985) p. 241 footnote 24.
[8] A. Stroud, *Christiaan Huygens and the development of the air pump*, Janus LXVIIII (1981) 136.
[9] A. van Helden, *The age of the air pump*, Tractrix 1, (1991) 149-172.
[10] R. Vermij, *Christiaan Huygen, De mathematisering van de werkelijkheid* (Veen Magazine, Diemen 2004) p. 87.
[11] In his book, *Harvard Case Histories in Experimental Sciences* (Harvard Univ 1957), J. B. Conant devotes the first 60 pages to " Robert Boyle's experiments in Pneumatics". In this account, however, there is not a single mention of Huygens and is puzzling "anomalous suspension", thus giving a somewhat lopsided history of the experimental discovery of the physical properties of air.
[12] one cubit=.46 meter.
[13] Galileo *Dialogue Concerning two New Sciences*
Translated by Henry Crew & Alfonso de Salvio
(Dover Publications, New York 1954) pp. 14-17.
[14] W.E. Knowles Middleton *The History of the Barometer*
(Johns Hopkins Press, Baltimore 1964) pp. 10-12.
[15] Ref. [14] pp. 23-24.
[16] An ell was a unit used by tailors for the distance between the elbow and the wrist. This unit varied between 27 to 45 inches depending apparently on the typical arm length of people of different nationalities.
[17] Ref. [14], p. 23.
[18] Ref. [14], p. 29.
[19] Ref. [2], pp. 205-206.
[20] Huygens' Ouvres XIV 481-497.
[21] Ref. [2], pp. 210-220.
[22] *Ouevres Complétes de Christiaan Huygens* IV (La Haye, Martinus Nijhoff, 1932) pp. 174-175.
[23] Huygens also reported that "I saw my experiment of purged water in the void in a pipe of 7 feet in height, where the water stayed up without falling , succeeded 2 or 3 times, in the presence of Lord Brouncker, Mr. Boyle and of many other persons" (quoted in ref . [7] p. 252). Such a higher column of water, however, exceeded the height of his receiver, and required that an apperture be made on top of it. After the 7 foot tube was inserted in the receiver, it had to be properly sealed with wax, but this change is likely to have decreased further the efficiency of the air pump. Claims were also made for anomalous suspension of mercury, e.g. Boyle and Brouncker reported that well purged mercury would stand at a height of 52 inches without using an air-pump, ref. [7] p. 254.
[24] Quoted in ref. [7] p. 252.
[25] It is generally assumed that the water column starts to fall because the pressure due to its weight exceeds the pressure due to the air remaining in the receiver. However, normal water contains dissolved gases which are released at low pressure. When air is first evacuated from the receiver, the water column starts to fall when the pressure due to the gas released inside the tube exceeds the pressure of the air remaining in the receiver. To regain pressure equilibrium, the gas inside the tube, according to Boyle's law, must expand thus pressing the water column down.

[26] A video of this experiment can be seen at $https://www.youtube.com/results?search_query=nauenberg2$, or at www.physics.ucsc.edu/ michael

[27] In 1662, Boyle published the results of this experiment, as well as arguments against Hobbes and Linus, as an Appendix to the second edition of his book [1]. In 1665, Hooke also published similar results in his book *Micrographia*, reprinted in R.T Gunther, *Early Science in Oxford* v. XIII (Dawsons, London, 1938) pp. 224-228.

[28] Hooke first conjectured the $PV =$ constant relation by the observation that during each cycle of his pump, the air density in the receiver decreased by a factor $V/(V+V')$, where V is the volume of the receiver and V' is the volume of the pump, and that , likewise, the height of his Torricellian column (with mercury) decreased approximately by the same factor. Boyle also credited this conjecture to Richard Towneley and to Lord Brouncker. see ref. [11] p.54.

[29] Huygens' Ouvres XIV 431-442.

[30] Leviathan, p.241, footnote 24.

[31] Leviathan, p, 344