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LIFE AND PHYSICAL DISCOVERIES OF TORRICELLI

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Following the resolution of the World Council for Peace, the 350th birthday of Evangelista Torricelli, the outstanding Italian scientist, was celebrated this year by the entire civilized world. Many Soviet organizations — The Physics and Mathematical Division of the U.S.S.R. Academy of Sciences, the Institute of History of Natural Sciences and Technology of the U.S.S.R. Academy of Sciences, the Union of Soviet Societies for Friendship and Cultural Relations with Foreign Countries, the "U.S.S.R. — Italy" Society, the Soviet Committee for the Maintenance of Peace — held a joint session on October 16, 1958 to commemorate this outstanding date. The introductory address was delivered by Academician N. N. Andreev; a paper "Torricelli as a Mathematician" was delivered by corresponding member of the Academy of Sciences of the U.S.S.R., B. N. Delone; Professor V. P. Zubov lectured on Torricelli's experiments in Florence.

EVANGELISTA Torricelli, one of the most remarkable scientists of the 17th century, passed through the world of science like a flashing meteor. This Italian mathematician, physicist and mechanist died in the very bloom of his creative forces and talent, at the very zenith of his fame, before reaching his 39th birthday.

Torricelli was born on October 15, 1608 near the small town of Faenza to a very poor family. He lost his father early and was brought up by his uncle, a Benedictine monk, of St. John's Monastery in Faenza. Later Evangelista studied philosophy, mathematics, and physics in a Jesuit school in his home town for two years. He showed his unusual mathematical capabilities early and in 1628, at his uncle's recommendation, he was sent to continue his education with an outstanding mathematician, one of the talented students of Galileo, the influential Abbot Benedetto Castelli, who at that time was tutor to the nephew of Pope Urban VIII at the Vatican.

Abbot Benedetto Castelli (1579-1643) entered the Monastic Order as a youth, but devoted himself entirely to scientific research. Along with great discoveries in various branches of mathematics, Castelli was the first to formulate the scientific foundations of hydraulics.

Castelli's students included Torricelli's contemporary, the outstanding physicist, astronomer and physiologist, Giovanni Borelli (1608-1670) and the great mathematician Bonaventura Cavalieri (1598-1647).

Castelli highly regarded young Torricelli and undertook the guidance of his education along with insuring his support by appointing him his personal secretary.

In 1632, an outstanding event occured in Italy's cultural life. In January of that year, Galileo Galilei published his outstanding book "Dialogue on the Two Most Important Systems of the World, That of Ptolemy and of Copernicus" (Dialogo sopra due Massimi Sistemi del Mondo Tolemaico e Copernicano).[2] Written in Italian so as to be accessible to any literate person, and presented in a highly artistic style, this book by Galilei rapidly found its way to the minds and hearts of large circles of the educated Italian society.

It should be noted that even long before the publication of the "Dialogue" there was a stubborn struggle in Italy between the adherents of Galilei, as the exponent of the revolutionary traditions of the Renaissance on the one hand, and the faithful representatives of the Catholic reaction on the other. This struggle flared up in 1610 when Galilei published his book "The Stellar Herald," where he first briefly reported his astronomical observations, made with the aid of the telescope he created, and where he first came out clearly in favor of the Copernican system. Even then the adherence of progress started to call themselves "Galileists." However, in 1616 the "Holy Congregation of the Sacred Cardinals" pronounced as "false and in complete opposition to the Holy Script the Pythagorean theory of the motion of the earth and the stationary sun, as taught by Nicolai Copernicus," and prohibited all the books containing this theory, lest it "gradually propagate further to the destruction of the Catholic truth."[3]

The appearance of the "Dialogue" in 1632 revived the struggle and the church obscurantists again started to demand insistently the prohibition of the seditious book by Galilei, who again allowed himself to discuss the problem of the truth of the Copernican system, a problem not subject to discussion as already resolved by the church. Apparently Galilei wrote a letter, since lost, asking aid from his former student and friend Castelli. But the letter did not find Castelli in Rome, and the latter's 24-year secretary took advantage of this occasion to strike up an acquaintanceship with the great Galilei. On September 11, 1632, Torricelli wrote Galilei a letter (reference 4, Vol. III, p. 35) that begins:

"Most worthy and honored Signor:

In the absence of our master, the most reverend father of mathematics, I, his most unworthy student and servant, who has the honor of being his secretary . . ." Toricelli acknowledges receipt of Galilei's letter to Abbot Castelli, and reports that he became acquainted with its contents in accordance with instructions given by his master. "I can assure your honor that the Father Abbot has always attempted to defend your honor's 'Dialogue' in all cases, both to the ruler of the Holy Court, with his entourage and to other ecclesiastic persons . . . I became fully acquainted with this matter. I myself am a mathematician, albeit young, a student of the very reverend father for six years. For the first two years I studied with the Jesuit Fathers. I have thoroughly and continuously studied, to this day, the book by your grace with great delight, at first in the house of the Father Abbot and then in Rome. Such delight can be experienced only by one who has thoroughly mastered geometry, Appolonius, Archimedes, and Theodosius and who has also studied Ptolemy and all the works by Ticho* and Longomontanus,† who finally, persuaded by the large number of coincidences, reaches Copernicus and who is in specialty and conviction a Galileist . . ."

Torricelli reports to Galilei in passing how unfavorably certain highly-placed papal officers look upon his Dialogue. In particular, he mentions malicious remarks by the Jesuit Scheiner, who later on was one of the initiators of Galilei's trial.

Torricelli finishes his letter with the following enthusiastic words: "I consider myself the happiest man in the world for being born in this century, when I can know and correspond with Galilei himself, the oracle of nature, and when I can have the favor of being related and guided by Ciampoli himself." *

*Ticho Brahe.

†Probably in error for Regiomontanus.

We don't know how Galilei answered his ardent fan or whether he answered him at all. Torricelli's preserved records show a tremendous gap following this letter, covering almost 9 years — to January 1640.

There are no data indicating the cause of this gap. However, the historical events that took place during that period and certain meager data do give grounds for certain assumptions regarding this matter.

What happened after September 1632? The sale of the Dialogue was already prohibited at the end of this year. Galileo's trial in the beginning of 1633 began and ended, as is known, in his public denial (June 22, 1633) of the "Heretic Theory of Copernicus." The great scientist was officially made a "prisoner of the inquisition." He was deprived the right of printing anything or discussing any problems on the motion of the earth. From 1634 through 1641 Galilei was under a careful supervision of the inquisitors in his own villa Arcetri near Florence, where he was isolated from his friends and students. We note, however, that the embattled churchmen did not confine themselves to persecuting the author of the Dialogue alone. In November 1632 the well-known litterateur and patron of the arts, an ardent adherent of Galilei, the canon Giovanni Bastista Ciampoli, whose name was so reverently mentioned by the young Torricelli in his first letter to Galilei, was removed from his position as the secretary of Pope Urban VIII. It was none other than Ciampoli who helped Galilei in 1632 to obtain the censor's permission to publish the Dialogue, thus causing the anger of Urban VIII.

The disillusioned Ciampoli, as he himself indicated, was "cut off from the world in a deaf corner of the Appenines." The last years of this period he lived in the small town of Fabriano.[6]

Torricelli's letters of 1640-1641 are also dated in Fabriano. It seems thus that Torricelli spent at least two years in this dead corner, where the disgraced canon Ciampoli was forced to live. Apparently Torricelli performed secretarial duties there. In the letter of January 5, 1641 Torricelli writes from Fabriano to his friend Magiotti that he has finally recovered from his sickness, of which he "nearly died against his wishes," and during his sickness there were accumulated "more than 200 letters which I must answer for my patron." The

*Cf. below.

name of the patron remains unknown.

In March 1641, finally free of the supervision of the inquisition, the blind and seriously ill 78 year old Galilei received a letter from Castelli, in which the latter reports that he plans to visit him enroute in Florence in order to show him his new book, and also "another book written by one of my students who, after learning the first principles of geometry, was my student for ten years and made such progress that he proved many theorems on mechanics, previously proved by your eminence, but in entirely different ways (reference 4, Vol. III, page 46).

Finally, on March 15, 1641 Torricelli sent Galilei a new letter, from which it is seen that Castelli has sent to his great teacher Torricelli's "De motu gravium naturaliter descendentium ..." (On the Motion of Heavy Bodies, Descending in their Natural Manner).

Torricelli writes in this letter (reference 4, Vol. III, pages 48-49):

" ... your emminence's papers are more worthy of admiration than of comments. I was seized with the greatest amazement from the very first day that I succeeded in seeing your books. However, your latest book on relative motion* has caused more boldness than amazement."

Torricelli reports that he desires to publish a small book in Rome or in some other city but wishes first to present it to Galilei for review. "I wrote these folios not because I intend to advance some doctrine of my own, but out of necessity to set down a memorandum for my small mind and out of desire to show my distant teacher with what enthusiasm I studied his theory in his absence." Torricelli then asks Galilei to consider this composition "as an essay like you, were you still a student, would write on poems from the Aeneid or on the speeches of Marcus Tullius."†

He begs to remain his servant "and although convinced that I am inferior to Magiotti and Nardi"‡ in my abilities, however, I excel them in paying immeasurable homage to the famous name of Galilei, a name universally known forever ... Will your emminence excuse my lack of education, my style, and the unlimited errors, particularly in the second part, which has not been copied but is a first draft, written rapidly, and I myself have not yet reread it ..."

Having visited Galilei in Arcetri, Castelli warmly recommended that he receive Torricelli and use him for the development, publication, and further advancement of his unfinished research. Galilei read Torricelli's book "On Motion," highly praised it, and asked Castelli that he send the young author to him. Torricelli could not move to Galilei immediately. Only by the end of September of that year did he set on his journey and arrived in Arcetri during the first days of October. Vincenzo Viviani, Galilei's biographer and student, who lived in Arcetri, reports that "Galilei immediately undertook to discuss with him one whole "Day" in the "Dialogues." Some material of the Dialogues was contained in his notes and some only in his thoughts, and Galilei intended to incorporate them in his Dialogues in the form of two "Days," to be appended to the previous four, published several years earlier in his book on the two new sciences of mechanics and local motion ... But Galilei died only some three months later, (January 6, 1642), after Torricelli barely started his work on the fifth Day. This sad event, which Torricelli did not expect at all so soon, left him in somewhat of a stupor ... and when he finally decided to return to Rome, he received instructions to await the orders of the Grand Duke who at that time was in Pizza, for he was appointed Mathematician to His Highness. Thus," continues Viviani, "the lectures on mathematics in the local lecture hall, which date back to antiquity but were interrupted for a long time, have been resumed."[7]

Let us recall that Torricelli's predecessor as professor of mathematics of the Florence Academy, starting with 1610, was Galilei, whose lectures were stopped by the orders of the inquisition in 1633. Thus Torricelli received the title previously held by Galilei, "Philosopher and First Mathematician of His Highness the Grand Duke of Tuscany" and simultaneously assumed the duties as Lecturer of Mathematics at the Florence Academy of Sciences (Accademia del Cimento). This was followed by the title of Lecturer on Military Fortification at the Florence Academy of Design (Accademia del Disegno). The material situation of the 32 year old Torricelli was suddenly improved. While previously the modest secretary could engage in theoretical investigations only in his free time, in Florence he finally found it possible to apply some of his ideas in the field of experiment. Here Torricelli apparently gradually completed work on Galilei's supplements to his "Dialogues" (Days V and VI). However he didn't succeed in getting them published. The "Fifth Day" was published by Viviani in 1674 and the "Sixth Day" only in 1718. The name of Torricelli is not mentioned in these, and exactly how much he has really contributed is not known.

As the Court's Natural Experimenter (Philosopher) and Mathematician Torricelli settled in apartments of the old palace of the Medici's in

*He refers to the "Dialogues."[1]

†I.e., Cicero's.

‡Galilei's students.

Florence. His place became the meeting ground for outstanding artists and scientists. Torricelli struck a particular friendship with the known artist Salvatore Rosa and with the known hellenicist Carlo Datti. The catalogue of Torricelli's personal library, a catalogue preserved to this day, lists, along with various works on mathematics, physics, astronomy, mechanics and military affairs, also a considerable number of artistic literary works.

Torricelli's biographers emphasize that he himself was not a stranger to literature and wrote sharp epigrams and comedies, which however were lost. In one of these epigrams in Latin, he pokes fun of some constructor who built a bridge which collapsed before completion. This epigram ends in a bitter complaint on the evil times that give rise to stupid bridge builders — ponti-fices (the plural of pontifex). However, any one who has studied Latin knows very well that the ancient Latin work pontifex (high priest) is the official title of the Pope. Torricelli's epigram became very popular in Italy as an allusion to Pope Urban VIII, who vainly attempted to save the churches' failing power by repression and persecution.

In 1644 Torricelli published first some of his papers on geometry and mechanics, on which he worked sporadically all these years. His name became widely known in the entire scientific world. The greatest scientist in Italy and abroad acknowledged Torricelli as a first-class mathematician. Apparently Torricelli's name does not remain unnoted in the literary awards. The Academia della Crusca in Florence, an institution specially dedicated to cultivation of beauty and purity of Italian literary speech, elected Torricelli a member and invited him to deliver a series of lectures. The mathematicians Magiotti and Cavalieri, learning of the honor accorded to their colleague, made quite a few sarcastic remarks in personal letters written to him concerning the Academicians of della Crusca, who were quite unversed in mathematics and physical sciences (reference 4, Vol. III, pages 74-75). However, these remarks did not worry Torricelli and he delivered 12 popular lectures on a variety of topics at the Academy della Crusca. In one of these lectures, "In Praise of Mathematics," Torricelli did not hesitate to ridicule "philosophers who consider themselves born to science and knowledge" but who turn out to be quite ignorant of machinery and equipment that is perfectly well understood by simple uneducated persons. These lectures were published by the Academy only in 1715.[16] These lectures were preceded by a curious note, stating that the authorities of the Academy, having become acquainted with the text of the "lectures" of Evangelista Torricelli, "have observed no errors in language in these lectures." Consequently, these lectures have been acknowledged to be a model of irreproachably pure Italian speech. In this matter, too, Torricelli turned out to be a worthy successor of Galilei, whose Dialogues are considered today to be undying memorials of not only science but also of artistic prose. "The academic lectures" of Torricelli were unfortunately not translated into other languages and are now little known. They differ from Galilei's "Dialogues" in a certain florid style, but are nevertheless authentic works of art. Six of these 12 lectures are devoted to physical problems and deserve most serious attention both as a popular discussion of the views and of the most important physical research of Torricelli, which will be discussed later. At the same time, Torricelli's "Academic Lectures" are thoroughly saturated with the bold aggresive spirit of the renaissance, struggling against the "peripatetic philisophers" i.e., against the adherence of the obsolete ideas of Aristotle, officially recognized by the dogma of the Catholic Church as unique and infallible. Although nothing is mentioned of Copernicus in these lectures, nor of cosmology as a whole, Galilei's merits are ardently hailed many times. The lectures "On Lightness" and "On the Wind," as we shall see, are directly related to Torricelli's famous experiemnt which led him to the invention of the barometer in 1644.

The great Duke of Tuscany, personally present at the demonstration of this experiment, issued on this occasion a special decree in which it is stated: "Whereas Evangelista Torricelli, thanks to his valor and success in realizing this matter; whereas he discovered the truth; whereas he overcame the fear of vacuum; whereas he extended the boundaries of science, we announce glory to the immortal God and triumph to Evangelista Torricelli.[11]

During his sojourn in Florence, Torricelli developed a new method of making glass lenses for telescopes. The Torricelli lenses were acknowledged during that time to be unsurpassable and the method of their manufacture was kept in strict secrecy by the Grand Duke. One must not forget that in the 17th century spy glasses were a paramount military significance, for they made it possible to watch the enemy and to warn against a sudden attack. In one of his letters (May 1, 1644) to the French mathematician and physicist Mercenne (1588-1648) Torricelli describes his activity in Florence in the following words: "Two parts of my book were already printed, and the remaining two parts progress more slowly, since I am exceedingly busy either in the telescope-lens shop or else constructing from day to day various machines and setting up different physical experiments, both under the orders of my master the Grand Duke."

During this five year's stay in Florence, Torricelli was thus able to carry on tireless work in the field of physics and engineering. However the heavy load exhausted him more and more. In October 1647 Torricelli took to bed, plagued by "fever" and terrible headaches. The condition of the sick man became worse and the headaches became unbearable. Torricelli fell into a "senseless furious delirium," in the words of his friend, Sirenai, who wrote to Torricelli's brother on the impending catastrophe. On October 24, 1647 Evangelista Torricelli died.

Apparently, at the very beginning of his sickness Torricelli detailed his method of polishing lenses in a secret letter addressed to the Grand Duke, at the latter's request. In one of his conscious moments he dictâted a detailed communication. He entrusted to his friends Cavalieri and Ricci the publication of all his unpublished manuscripts. He asked to be buried without any honors, but in the Basilica of the Church of St. Lawrence in Florence, "if the Canon Fathers will consider me worthy."

Not one of these wishes in Torricelli's last will were fulfilled. Cavalieri died a month after Torricelli, and Ricci could not find a publisher for the manuscript. The unpublished manuscripts of Torricelli's works and notes were handed down from person to person as late as the 18th century and were finally sold — to a retail shop for wrapping paper. A certain Clemento Nelli, who bought sausages in the shop and took home the wrapping, noted on it with astonishment an autograph by Galilei. He bought the rest of the manuscripts, hoping to publish them, but did not succeed. In 1818 the Torricelli manuscripts were purchased by the reigning Duke of Tuscany and in 1861 they were finally deposited in the National Library of Florence. Only in 1919 were these remaining manuscripts published. Apparently, the best preserved were the mathematical papers. A considerable portion of the papers on physics, mechanics, and engineering and all his literary works were irretrievably lost (reference 4, Vol. I, p. 15).

The canons of the Basilica of St. Lawrence apparently did not believe Torricelli "worthy" of burial in the church. He was buried somewhere near the church with other simple parishoners. The Grand Duke planned to erect a memorial stone on his grave but never got around to it. Torricelli's grave was thus lost.

Let us turn now to Torricelli's physical discoveries. It must be emphasized that they have not yet been studied in their entirety. The preserved researches of Torricelli cover the following branches of physics: particle and body mechanics, hydromechanics, physics of the atmosphere, geometrical optics, and the technology of lens manufacture. Torricelli's principal works on particle and body mechanics are contained in his "On the Motion of Heavy Bodies Descending in a Natural Way and of Projectiles" (De motu gravium naturaliter descentium et projectorum), in three "academic lectures" "On Impact" (Della percossa), and in unpublished manuscripts collected under the name "Various Data on Motion and Momenta" (De motu ac momentis varia).

The treatise "On the Motion of Heavy Bodies" is originally a strictly systematized treatment of Galilei's views, stated by him in popular form in his "Dialogues and Mathematical Proofs Concerning two new Branches of Science, pertaining to mechanics and local motion."[1] However, when published in 1644, Torricelli's essay contained a development of certain premises and an expansion of this essay. Thus, he develops problems of external ballistics to a greater extent than Galilei and gives more detailed tables of the superelevation of guns. The corresponding parameters of projectile trajectories which Galilei uses as an illustrative numerical example of parabolic motion, acquires a more practical character in Torricelli's work. The entire treatment of this problem is used by Torricelli clearly to help in a direct application of his tables to artillery.

Reviewing Torricelli's research on the motion of heavy bodies, the well-known Italian physicist R. Macolongo indicates[8,9] that Torricelli set out above all to prove Galilei's postulate that bodies that fall along slightly inclined planes from equal altitudes should have equal velocities. Torricelli's new proof of this postulate is based on the principle of the center of gravity, predicted by Galilei, but included by Torricelli in a more general principle: "Two heavy bodies cannot move by themselves jointly unless their common center of gravity descends." From this postulate Torricelli derives Galilei's famous theorem on the motion of two weights interconnected by a string running over a pulley. The next novelty introduced by Torricelli, as indicated by Marcolongo, is that no matter what the superelevation, the trajectory of a projectile is a parabola. Torricelli proves Galilei's entire theory of motion of projectiles in a simple manner and at the same time more rigorously, using the geometrical method in a consistent manner.

Many of Torricelli's papers, dealing more in mathematics than in mechanics, are devoted to the problem of finding the center of gravity of various plane figures and bodies. This problem was the topic of Torricelli's correspondence with Cavalieri and Ricci. Torricelli, as is known, developed the so-called "method of indivisibles," proposed by Cavalieri, and first treated this method in clear and understandable form. In this field, Torricelli along with Cavalieri, deserves being called the predecessor of Newton and Leibnitz in the discovery of infinitesimal analysis.[10]

As a rule, those studying Torricelli's papers on mechanics omit his popular lectures on percussion. Yet these lectures contain quite a number of deep physical ideas, which are of undoubted historical interest.

"The force of percussion, writes Torricelli, belongs among the most effective of all the discoveries of mechanics, and is probably the most hidden and the most obscure of all the secrets of nature." (reference 4, Vol. II, p. 5).

Torricelli then proceeds to repeat essentially the contents of the Sixth Day of the "Dialogues." But Torricelli goes deeper and develops further the individual problems raised by Galilei in his "Dialogues."

Thus, comparing the pressure of a heavy body at rest with the pressure arising upon impact of a falling body, Torricelli dwells in particular on certain properties of gravity. "The gravity of the bodies of nature is the source from which momenta continuously originate," writes Torricelli, "and a heavy body creates force at every instant . . . " Torricelli, uses, essentially, Galilei's terminology, defining a moment as "that force, that effort, that action with which the mover moves and the moved body resists." (reference 1, remark 22). Torricelli indicates that gravity is the perpetually discovered "source of momenta," which "at any given instants of time or (if you don't like the word instant) at any briefest time interval produces a moment equal to the absolute weight of a given body . . . and in fact, when heavy bodies are at rest," continues Torricelli, "all these momenta (impeti) . . . are annihilated by the supporting body, which, without concealing its opposing action, continuously suppresses all these nascent momenta. However, when the same heavy body fall in air, all these momenta are not suppressed, but are retained in it and multiply." (reference 4, Vol. II, p. 15).

This splendid description contains practically the entire concept of force as being the momentum acquired by the body within a certain brief time interval.

In his discussion of the momentum of a moving body, Galilei indicated that this momentum is determined by the weight and velocity of the moving body. Torricelli goes further. He replaces the word "weight" by a new definition — quantity of matter (la quantita della materia) (reference 4, Vol. II, p. 25), thus coming close to the concept of "mass" proposed by Newton 40 years later. In explaining the role of this "quantity of matter" in the reaction of a body to impact, Torricelli remarks: "There is no doubt that the matter itself is dead and serves only to prevent an acting force by opposing it. Matter is none other than Circe's vessel, sung about by the poets, which serves only as a container for the force, momenta, and impulse. The force and the impulses are such thin substrata, such imaginary quintessences, that they cannot be contained in any other vessel than the bodily nature of the natural solids. This is my opinion, "emphasized Torricelli," since the human force appears only in what he works upon and what he touches" (reference 4, Vol. II, p. 27). The above quotations are enough to show that Torricelli's lecture "On Percussion" contains material of interest to the historian, evidencing, in our opinion, that Torricelli was much closer than Galilei to the 18th century concepts of mechanics.

The second book of the treatise "On the Motion of Solid Bodies. . . and Projectiles" Torricelli includes a small section "on the motion of water" (reference 4, Vol. II, pp. 185-197). Here we have for the first time Torricelli's famous problem on the shape of a stream of liquid flowing from a vessel. The solution is based on the following assumption: Water which escapes abruptly has, at the point of escape, the same momentum (impetus), as would have some solid body or a single drop of water, were it to fall in a natural manner from the uppermost surface of the water to the opening from which it escapes." Proving next that the trajectory of such a drop will be a parabola, Torricelli notes that experiment "confirms to some degree our postulate." He then dwells on this experiment. A horizontal nipple with small vertical holes is placed in the bottom of a large vessel. If the holes are first sealed with the finger and then uncovered, it can be seen that the first drops breaking away from the hole rise to the level of the water in the vessel and describes a parabola. Torricelli correctly explains why the crest of the water jet lies just below the level of the water. He next indicates that if someone has the facility to verify this principle experimentally, it should be done not with water, but with mercury "since it has a greater internal gravity," i.e., a greater specific gravity. Then Torricelli describes "an experiment which confirmed almost all the details of our premises" (speculatiunculas). The height of the vessel, made in the form of a parallelopiped, exceeded "a geometrical pace" and the area of the bottom was not less than that of the palm. A round tube led out of the vessel. "The holes were in fact round, somewhat larger than the human pupil and were not made roughly, but drilled very carefully in copper thick plates, vertically mounted. The water which escaped vigorously always left perpendicular to this plane, from which it broke away, and it was therefore necessary that the outlets from our tube be horizontal."

The experiment has shown that a jet of water that breaks away horizontally curves into a parabola (reference 4, Vol. II, p. 188).

The important factor, naturally, is that Torricelli's premise is based on the law of conservation of momentum. Neither Torricelli nor Galilei formulated quantitatively the dependence of the momentum of the mass and velocity, and it can therefore hardly be said, as is done by several investigators, that Torricelli, like Daniel Bernoulli, began with the law of conservation of the "live force" (mv^2). Both Galilei and Torricelli were already very close to the concept of "live force," but its mathematical expression remained unknown to them.

However, Torricelli not only showed that a jet escaping laterally from a liquid-filled vessel assumed the form of a parabola, but also proved that the speed of the escaping liquid, meaning also its quantity was definitely related to the height of the column of liquid above the opening. He came to the conclusion that the speed is proportional to the square root of the height. Torricelli was not yet acquainted with the formula $v = \sqrt{2gh}$, first given by Johann and Daniel Bernoulli almost a century later. Torricelli uses $v = A\sqrt{h}$, where h is the height and A a certain constant; he thus gets $v : v_1 = \sqrt{h} : \sqrt{h_1}$.[12]

Along with research on the principle of hydromechanics, Torricelli is responsible for several outstanding projects in hydraulics, directly connected with the development of water-power structures on the control of the flow of the river channel. This set of problems, however, is outside the scope of this article.

We now turn to Torricelli's investigations in the field of the physics of the atmosphere. The principal problems in the physics of the atmosphere were then the problem of whether air has any weight and the problem of the origin of wind. Torricelli rendered great services in both problems. In all probability Torricelli wrote an unpublished report of his investigations, which was not preserved. The description of Torricelli's famous experiment with the barometer was actually preserved only in the form of a private letter addressed to Ricci (reference 4, Vol. III, p. 186). The problem of the weight of the atmosphere and of the origin and nature of wind is mentioned only in the popular lectures, delivered at the Academia della Crusca.[16]

At that time the problem of the weight of the atmosphere had a history dating back for several centuries. Aristotle stated that "everything in its place has weight, with the exception of fire and air." (Ἐν τῇ αὐτοῦ χώρα, παντα βάρος ἔχει, πληην πυρὸς καιὸἀήρ) (p 13). During these centuries some authors expressed themselves in favor of Aristotle, and others, to the contrary, were decisively in opposition. Thus, Galilei in his earlier work "On Motion" (De motu) indicated that "in spite of Aristotle's opinion, one cannot call something merely light or heavy ... all bodies have weight, some more and some less, depending on whether their matter is compressed and packed together or diffused and rare."[13] This problem was analyzed in detail by Torricelli in his two lectures "On Lightness." Here he first criticized severely Aristotle's premise that absolutely heavy bodies tend to their "natural place below," where they come to a state of rest. On the other hand, absolutely light bodies like fire, tend, according to Aristotle, to go upward. "It is no news to me," said Torricelli, "that specially prepared mirrors gather the rays of light and that certain vessels and rooms concentrate the lines of sound in a single point. But that it is to me novel, unthinkable, and unheard of is that nature would endow the world with some internal principle of motion towards the center, towards a single point with a trend towards an eternal catastrophe" (reference 4, Vol. II, p. 44). "It is quite impossible," says Torricelli ironically, "that the elements of the earth and water could ever reach this cherished center and fall into it." Refuting Aristotle's idea as absolutely absurd, Torricelli insists on a formulation identical with that of Galilei: all bodies have weight.

The problem of vacuum has been closely connected with the problem of the weighability of air since ancient times. According to Aristotle, the concept of vacuum contains a logical contradiction, for "a place without a body located in it" cannot exist. For many centuries the greatest scientists have stated that vacuum is impossible in principle. Ibn-Sinna (Avicenna), for example, stated that if a vacuum would form anywhere on earth, the sky itself would split and descend to the earth in order to fill this vacuum. Thus there has gradually grown the conviction that nature experienced a sort of fear of vacuum (horror vacui). By vacuum was meant a space containing no air. It therefore became an axiom that it is impossible in principle to obtain a space without air. Galilei also adhered to this point of view in his "Dialogues" using as an example the sticking of two plates: "This experiment clearly shows that nature does not desire, for the shortest interval of time, the formation of a vacuum that would be produced between the plate until the instant when the surrounding air would occupy the corresponding space: . . . the resistance to the formation of vacuum, like that observed in the example of two plates in close contact, undoubtedly exist between different parts of one solid body and is at least one of the causes of its adhesion" (reference 1, pp. 63-64). This problem is considered further in the "Dialogues" in connection with the discussion of the impossibility of raising water with a pump to a height more than 18 cubits. Galilei was not only firmly convinced that air has a weight in principle, but was first to determine experimentally the specific gravity of air by means of a very clever experiment, described in the "Dialogues" (reference 1, p. 170-171). At the same time Galilei stated that the upper layers of the air need not press on the lower ones. The principal argument was an incorrect statement by Galilei that the pressure experienced by a solid in water independent of the height of the liquid column above it. He assumed that "water has no gravity at all in water . . . and if water in water weighs nothing, how can the lower layers be compressed by the upper ones?" Galilei used this erroneous statement to draw analogous conclusions regarding the atmosphere. "Note that all of the air in itself and above water weighs nothing . . . it is not surprising that the entire atmosphere weighs nothing, since the situation is exactly the same with water."[17] Galilei saw a weighty argument in favor of his theory in the fact that a fish does not feel the weight of the water and in the fact that neither animals nor humans feel the weight of the atmosphere. Denying a priori the possible existence of atmospheric pressure, Galilei was forced to look outside the atmosphere for the cause of the observed fact that no single piston pump could lift water to a height greater than 18 cubits.

Thus, Galilei ascribed a principal role in this fact to the circumstance that the nature so to speak opposes the appearance of vacuum. He concluded that the water column is acted upon, on the one hand, by the ill-famed resistance to the appearance of vacuum, which drags this column upward, while the weight of the column itself pulls it downward. As the water column lengthens "it breaks of its own gravity, the same as would occur with a string . . . " He furthermore says: "After determining the weight of water contained in 18 cubits of the pump pipe, no matter what the diameter of the latter, we can determine the value of the resistance to the formation of vacuum in a strong cylinder made of any material" (reference 1, page 72).

This theory of Galilei was refuted by some of his contemporaries. Thus Descartes, who was in the Netherlands in 1639, and who obtained from Galilei a personal copy of the "Dialogues," wrote to Mercenne: "What he ascribes to vacuum must be ascribed to none other than the weight of air. One can be assured that were the horror of vacuum to prevent the separation of two bodies, there would in general exist no force capable of separating them."

Shortly before Galilei's death the Parisian mathematicians sent him several remarks concerning his "Dialogues": "We believe that vacuum in no way prevents the separation of two polished spheres placed one on top of the other. This is rather done by the air, which presses on the top and on all sides" (reference 13, pages 99-100).

In 1644 Torricelli undertook in Florence an experimental investigation of air pressure. "I emphasize," wrote Torricelli on June 11, 1644 from Rome to his friend Ricci, "that I had no intention to make a philosophical experiment with respect to vacuum, nor merely produce this vacuum, but simply to produce an instrument that would show the variations in the air when it is heavier and denser and when it is lighter and thinner. Many have said that vacuum cannot be realized, and others that is is realizable with difficulty owing to a resistance on the part of Nature. I have observed the following: there is a principal reason for this. This reason, so to speak, prevents formation of vacuum. I believe it purposeless to attempt to ascribe to vacuum an action that is clearly caused by a different cause. Having made reliable and very simple calculations, I find that the reason proposed by myself (namely, the weight of the atmosphere) could in itself cause a greater resistance than it does produce, without resorting thereby to vacuum . . . We live submerged on the bottom of the sea of the elementary atmosphere. Experience shows without any doubt that this atmosphere has weight and the weight is furthermore such, that being at a maximum near the earth's surface, it equals approximately 1/400 of the weight of water . . . It is natural, the weight of the air is experienced at this bottom both by humans and animals, and that on the peak of a high mountain the air begins to be purer and much lighter in weight than 1/400 of the weight of water" (reference 4, Vol. III, pages 186-187).

Torricelli then describes in great detail the famous mercury-tube experiment which by now has become a conventional classroom demonstration. At first the experiment failed, but then Viviani, helping Torricelli in this research, overcame all the difficulty. Taking a tube two cubits long, the investigators filled it with mercury and covered the open end. When this end was uncovered, the mercury dropped and stopped at a level of $1^1/_2$ cubits. It was shown that this height was independent of the shape of the upper, sealed end. The instrument invented by Torricelli was named "barometer" by Mariott only in 1676.

It must be emphasized that the invention of the barometer was far from a chance result of Torricelli's investigations, but represented a logical and unavoidable conclusion of his work on the physics of the atmosphere. The extent to which Torricelli was far ahead of his time in this respect, can be readily seen from his lecture, "On the Wind." One must assume that in Torricelli's unpublished papers there are more detailed treatments of the investigations that served as the base for this popular lecture.

"The philosophers state," says Torricelli, "that the wind owes its origin to certain hazy evaporations from the moist earth. They noted that after rain the wind is usually stronger and lasts longer than ordinarily, and they therefore state that when the earth is covered with moisture the force of the sun rays and of the underground heat produces two sorts of evaporations, one moist, which is the source of the future rain, and the other dry, which produces the winds . . . But if all the rains should produce two sorts of evaporations, one serving to produce wind and the other for future rains, is it not clear to anyone that the matter making up the rains will continuously diminish, and the matter producing the winds will continuously increase? But let us go further, for since the school of the philosophers has mastery over the transmutation of elements, it will soon find an answer to this objection.

I personally doubt above all the observations themselves. It is actually known that after the rain the winds are most frequently northerly ones. However with respect to southern winds this rule is not only inaccurate, but very frequently quite the opposite takes place. The Sirocco winds blow during the day almost always before the rain, until it begins, and die down after it stops raining. And yet, according to the opinion of the peripatetics, they should blow stronger after the wind than at any other time, since the moist earth is more amenable to evaporation of the elements contained in it. Furthermore, in this case there should be evaporated from the earth a larger number of fogs and clouds, when both causes act simultaneously, i.e., during the warm season and the earth is moist. And when is there a more favorable conjuncture for wind to arise than after rain, when indeed the southern winds arise? It is then that we have water-filled cracks in the trees, flooded meadows, and heavy streams. What can be more? Even the insides of the houses are so damp in those days, that marble begins to sweat. Isn't there enough moisture available during that time of the year from the noontime disease-laden oppressive heat, when the sirocco carries with it heavy air, which literally seems to blow from a furnace, and everything alive, afflicted by the heavy heat, can hardly keep on its feet? To the contrary, in final analysis, the strongest north winds come after some other rain there. Yet, the dry air, subjected to the action of the northern cold, should not have enough force to lift a large amount of vapor, if what the philosophers say is true, that both heat and moisture are needed to produce wind. What can we say about winds that arise spontaneously, not preceded by any rain? Not only the speculative philosophers, but even uneducated wayfarers are aware of these winds, which occur at an exactly fixed time and which prevail reliably . . . " Torricelli then recalls the wind that regularly blows before the rise of the sun, the evening zephyrs, and the prevailing winds that blow in different countries during different times of the year.

Incidentally, he examines the opinion of the ancient scientists that "if a certain amount of water is converted into air in some manner, it expands by a factor of ten times and occupies ten times the volume." Torricelli speaks on this subject: Modern scientists, more inquisitive and thus more resourceful, have found through difficult experiments that if water is converted into air, it increases in volume not by ten times but by 400 times. Since this principle is now known, we see that not merely one rain, but even the entire ocean could not produce enough matter for the undefatiguable wind, that lasts sometimes eight or even ten days."

The moisture of rain, in Torricelli's opinion, is distributed in various ways and only a minute fraction of it evaporates. However, its volume is so large that, in expanding, it covers a great part of Europe. Were such a wind to blow, it could cover not only small Italy but also Spain and France and Germany, and all other countries, which all taken together amount to a rather large portion of the inhabitated world. The height of such a current or influx of air would reach at least three or four miles.

Refuting the speculations of the philosophers on the origin of the wind, Torricelli continues: "But isn't there some clear feature whereby to identify the true cause of winds, based on a single principle, which could be proved to exclude all others?

This principle is none other than the well-known and common principle of compression and rarefaction of air. The most venerable cathedral, Santa Maria del Fiore, and even more so the Rome Basilica, have the ability of ejecting, in the hottest summer days, quite a lot of fresh air through their own doors, at a time when the air is calm and there is no wind at all (on the outside). The reason for this is as follows: The air contained in the large building is for some reason cooler than the external air, which is heated by the strong direct and reflected rays of the sun. But if the air is cooler, it is also denser, meaning that it should also be heavier. This is why the air should indeed flow to the outside, and as much air flows in through the higher windows and flows out through the door. In the Rome cathedral during noon hours the freshness of the wind not only fails to caress, but even hurts. The wind from the doors of this cathedral is so strong that it causes a surprise.

Let us apply the same observation not to the closed volume but to the great extent of the open atmosphere... let us imagine that the whole northern hemisphere is quiet and completely at standstill, without a single gust of wind, without a single motion of the air. Let a sudden rain or some other cause, without changing anything in the remaining portion of the hemisphere, make Germany cooler than usual. Undoubtedly, the cooled air over this entire extensive country becomes denser. In order for it to become denser it is necessary that in the upper portion of the atmosphere above Germany there appear a certain emptiness, caused by the foregoing increased density. The air over the neighboring countries, being fluid, will try to fill this unexpectedly created emptiness. The upper portions of the atmosphere will then race, in the form of a wind, towards the cooler portion. But in the lowest region, i.e., the part of the air adjacent to the earth, an opposite flow will occur. In spite of the fact that Germany is already covered with dense air, the air there will become even denser, and, what is particularly distressing, will cause a motion of air everywhere ... Thus, wind should be in the form of a circulation that cannot be avoided over any limited portion of the earth. The effect of this circulation can continue as long as its cause exists."

A study of Torricelli's lecture "On the Wind," fragments of which we have just cited, show that to him belongs not only the honor of discovering the origin of the wind, but that he as early as in 1644 outlined the principles of the general circulation of the earth's atmosphere.

One can thus assume that the invention of the barometer was obviously only a portion of Torricelli's intensive program of experimental meteorological investigations, interrupted by his death.

Historians of science frequently assign priority in the invention of the atmospheric circulation to various scientists of the 18th century, losing sight of the fact that Torricelli's "Academic Lectures," first published in 1715 (and now almost forgotten), should have been well known to the scientists of the first half of the 18th century.

Let us now turn to Torricelli's optical research Not one paper by Torricelli on geometrical optics has survived. However, in the salvaged correspondence we find mention of the fact that Torricelli, like many of his contemporaries, worked on this problem. Of particular interest from this point of view is a postcript to a letter addressed to Ricci on February 6, 1644: "Yesterday I was in high grace of the Grand Duke, who presented me with a chain worth 300 scudi. His Highness was extremely pleased with my invention concerning the preparation of lenses, accomplished by geometric considerations in conjunction with a study and knowledge of conic figures and the science of refraction" (reference 4, Vol. III, page 167).

In a letter of February 16 of the same year, Cavalieri warmly congratulates Torricelli for "he discovered something new in the problem of refraction and concerning lenses for telescopes" (ibid). And in a subsequent letter dated March 15 Cavalieri reports that both he and his students and friends await impatiently news on the nature of this discovery, which has enabled Torricelli to manufacture lenses of unusual quality. However, we know that this invention was kept secret by the grand duke, and Torricelli never reported it to any of his friends. At the same time it is known that the lenses made by Torricelli were very famous during his time. Naturally, certain master opticians attempted to surpass Torricelli and to compete with him. However, any time that Torricelli's friends reported the arrival of a new master, Torricelli invariably answered that his lenses could never be surpassed.

Since the only description of Torricelli's invention, submitted by him to the grand duke before his death, has been lost, the great Italian optician V. Ronchi attempted in 1924 to clarify this problem by directly investigating the remaining authentic Torricelli lenses and the notes made in his own writing. Ronchi has subjected Torricelli's lens (10 cm diameter, focal distance 5.7 m) to the ordinary modern meniscus-surface tests by comparing it at the National Optical Institute with a standard modern lens, using a special interferometric instrument. Here is what Ronchi writes on this subject: "The attached photograph shows interference fringes between the surface of the Torricelli lens and the model optical surface. The regualrity of the concentric lenses shows that the surface finish of Torricelli's lens has the maximum desired optical accuracy; in general, it is at the limit of optical perfection."[14]

Analyzing this striking result, Ronchi finally concludes that the "secret" of Torricelli's invention in lens manufacture lies in his inventing a meniscus shape that produces minimum spherical aberration. Actually the genuine Torricelli lenses are in themselves evidence that this condition was satisfied in their manufacture. This conclusion becomes the more likely, since Torricelli remarks in one of his letters in passing that in solving the problem of lens manufacture he used a method he developed for finding maxima and minima.

What is also remarkable is that Torricelli found some method of testing the correctness of his lenses.

Our brief survey of the life and the physical research of the great son of Italy, Evangelista Torricelli, makes no pretense whatever of completeness. We should like, in conclusion, to recall that this remarkable figure, one of the outstanding founders of the modern science and an active fighter for its triumph, still awaits a biographer.

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Translated by J. G. Adashko