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Theories of motion and matter from Aristotle to Galileo

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We examine the metaphysical theories of motion and matter developed by Democritus, Plato, and Aristotle, as well as other theories that appeared later on and were great influenced by Aristotle. We distinguish two subsequent developments. One is the impetus theory for the projectile motion and the other is the void theory for the rise of liquids by suction. We analyze the Galileo theory of motion, emphasizing the crucial step in its development which was the precise definition of velocity. We also analyze the events related to the experiments of Torricelli, which was understood as the production of void, and his explanation based on the weight of the atmospheric air.
Keywords: Theories of matter and motion, Metaphysical theories, Aristotle, Galileo.

1. Introduction

Scientific theories underwent a great development in the seventeenth century [1–12]. A major development took place particularly in the theory of motion of bodies when Galileo proposed his kinetic theory of projectile motion and Newton introduced the dynamic theory of motion. Before Galileo, the theories of motion and matter evolved according to the thoughts developed by Aristotle called metaphysics, or as a result of criticism of them. Metaphysical theories appeared in the classical period of ancient Greece and were used throughout the middle ages [13–22]. They provide explanation of the real world through metaphysical propositions which, according to Carnap, claim to represent knowledge about the real essence of things and which are over and beyond all experience [23].

A scientific theory [24–27] is understood as an abstract framework equipped with a list of correspondence between the concepts of the abstract framework and their real counterparts, which are liable to be observed or measured experimentally [9]. At a first glance, we would think that all concepts of a scientific theory must have a real counterpart, and as a consequence we would be compelled to search for the real interpretation of all concepts. In fact, this is not necessary but these concepts must lead to other concepts that have real correspondences. The most striking example is the wave function of quantum mechanics, which has no real counterpart and for that reason is called non-observable. Another example is the deferent circle used by Ptolemy in his astronomy.

Let us compare a metaphysical concept with the concept of wave function of quantum mechanics and with the concept of deferent circle of Ptolemy. What distinguishes these three non-observable concepts? The wave function obeys a law, the Schrödinger equation, which leads to the spectral lines of hydrogen which are measured experimentally. The deferent circle of Ptolemy combined with another circle lead to a trajectory that explains for instance the retrograde motion of Venus on the celestial vault, which is observed and measured. In contrast, a metaphysical concept does not lead clearly and unambiguously to any concept that could be observed or measured experimentally.

When examining metaphysical theories, attention should be given to the terms used to denote the concepts of the theory. Some terms are the same as those used in the present scientific language. However, their meanings are usually different, being closer to those of the common language. For instance, velocity is simply ‘quickness of motion’ or ‘rapidity’, force is ‘active power’, power is ‘the ability to produce an effect’, gravity is ‘the quality of having weight’ [28].

Special attention should be paid to the meaning of the terms science and physics, which should be understood in their common senses. The common meaning of *science* is possession of knowledge as distinguished from ignorance or knowledge attained through study or practice [28]. The specific meaning of this word involves in addition theory and experimentation. As to the word *physics*, it comes from the Latin *physica* which in turn comes from the Greek *physikē*, which means nature [28]. Its original meaning is the knowledge of nature. The present meaning is the science related to what one calls physical phenomena.

In the following, we examine the theories of motion and matter developed by Democritus, Plato, and Aristotle, and some other theories that appeared afterwards which were greatly influenced by the ideas of Aristotle. These are the theories of Galen, Philoponus, Avicenna, and Buridan. We also examine the Galileo theory of motion, and the barometric experiments that occurred during the seventeenth century, particularly

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the experiments of Berti using water and that of Torricelli using mercury.

2. Democritus

In the fifth century BC a theory of matter appeared in the ancient Greece based on the assumption that the matter is discrete and that the primary constituents are indivisible and moves on the void. The theory was developed by Democritus from a suggestion made by Leucippus [18]. Democritus wrote a large number of works in several fields of knowledge but none of his writings survived from antiquity, except for a few fragments. His writings are known to have existed and the contents of some of them are known from the extant works of later writers. The comments and quotations related to Democritus and other Pre-Socratic philosophers can be found in publications containing selections of these works such a the one we use here [29, 30]. The comments on Democritus that we present below are mainly due to Aristotle.

Aristotle says that the elements are the full and the void, which together are the material causes of existing things. These elements differ by shape, arrangement and position. They escape our senses because they are very small but their aggregations become perceptible. Simplicius states that the first principles are infinite in number and that they are indivisible and compact. The indivisible bodies can be heavier in proportion to their bulk, says Aristotle. But Aetius is of the opposite opinion, that they do not possess weight and they move as the result of striking one another.

Aristotle states that the primary bodies are permanently in motion in the void and as they move they collide with each other and become intertwined and scattered. It seems that Aristotle meant an irregular and erratic motion. They may cling to one another and stay together for some time and then they apart if necessary.

A theory similar to that of Democritus just described was proposed by Epicurus who lived in ancient Greece in the second half of the fourth century BC and the first decades of the third century BC. His theory is not substantially distinct from that of Democritus [19], and emphasizes the indivisibility of the primary constituents. His surviving complete works consists of three lengthy letters, one of which is a letter to Herodotus (not the historian) [31], which contains the theory that we summarize below.

The universe consists of bodies and space. Some are compounds and some are those from which the compounds are formed. These are indivisible and unalterable. They are completely solid and cannot be dissolved. The indivisible bodies move continuously all the time, falling straight down, or swerving, or yet recoiling from their collisions. They do not possess the qualities of the perceptible things, except shape, size and weight.

An important aspect of his theory concerns the doctrine of swerve [16, 19]. Epicurus argued that the indivisible bodies travel in the void with the same speed independent of their weight. But if this happens, no collision is possible and the compound bodies could not be formed. To circumvent this problem, he states that occasionally an indivisible body deviates slightly from its original path, which is sufficient to encounter other indivisible bodies and to form a body.

The theory of Epicurus was described by the Roman poet Lucretius [16], who lived in the first century BC, in his poem On the Nature of Things [32, 33]. Maxwell gave a very clear account of Lucretius. In his second paper on the kinetic theory of gases of 1867 [34], he wrote: "In the exposition which he [Lucretius] gives of the theory of Democritus as modified by Epicurus, he describes the invisible atoms as all moving downwards with equal velocities, which, at quite uncertain times and places, suffer an imperceptible change, just enough to allow of occasional collisions taking place between the atoms. These atoms he supposes to set small bodies in motion by an action of which we may form some conception by looking at the motes in a sunbeam".

We have deliberately not employed the term atom to refer to the primary constituents of the Democritus theory as is usually done, for instance in the text of Maxwell quoted above. The term atom comes from the Latin *atomus* which is a loanword from the Greek *atomos* for indivisible or that cannot be cut. None of the Greek writers mentioned above used a specific term for the primary constituent. They did use the word *atomos* but to denote its essential property. Lucretius, writing in Latin, also did not use the Latin *atomus* but he used the Latin *primordia rerum* (first-beginnings of things) or *primordia* (first-beginnings) alone as his preferred term for the primary constituents [33]. But Cicero, the Roman writer contemporary of Lucretius, in one his philosophical writings [35], did use the Latin word *atomus* to refer to the primary constituent [33].

3. Plato

Plato [36] lived in the last quarter of the fifth century BC and the first half of the fourth century BC in ancient Greece. It is believed that the whole body of his writings survived from antiquity [37]. A Greek-Latin text of his works was published in 1578 [38], and a standard Greek text was published between 1900 and 1907 [39], and a standard English edition was published in 1997 [37]. We will refer to the passages of the Greek-Latin edition [38] by the notation [*ps*], where *p* is the page number and *s* denotes the section within the page.

His works are arranged in the form of nine groups of four books each, called tetralogies, comprising thirty-five books written in the form of dialogues and one book consisting of letters. Socrates is usually the leading figure of the conversations and in the Republic he is the one who expounds the philosophical ideas of Plato [36]. Timaeus is the name of one of the dialogues and of the spokesman for Plato himself [18]. In these dialogues we find a variety of subjects including metaphysics, epistemology, ethics, political theory, language, art, mathematics, and science [36].

We examine the subject related to knowledge which is contained in the Republic and Timaeus. His thoughts on this subject are based on the theory of forms or ideas. According to Plato, the physical world is not just the world recognized by our senses but is also the world of forms. For Plato, the forms are not representations as we might think but are the real world proper although intangible. In book ten of the Republic, he illustrates his thoughts concerning the forms by the following example. When we refer to the word *bed*, we should distinguish three cases. We may refer to a painting of a bed, or to a bed created by a carpenter, or yet to the form of a bed. Plato holds that these three circumstances constitute a series of increasing reality [36].

The cosmological scheme of Plato contains three elements: the forms, the sensible world, and the craftsman who is the agent that organizes the world in accordance with the model given by the forms [18]. Whether Plato believes in the existence of the craftsman or whether it is just an allegory, one cannot tell. In any case, we take the viewpoint that the agent is actually Plato, and not the supposed craftsman, in the sense that the theory of cosmology including the forms is an invention of Plato himself.

In the Timaeus, Plato advances the theories related to diverse subjects, such as astronomy, structure of matter, perception, and physiology. We examine here only the three first subjects. The specific theories are not his in their entirety. Plato based his views about these subjects on the ideas of his predecessors and contemporaries, such as Empedocles, the Phytagoreans and the atomists [18]. We note that the writings of these philosophers did not survive to modern times except for a few fragments. The existence and contents of their writings are known through the writings of other authors, particularly Plato himself.

We begin with his doctrine of the ultimate constituents of matter. The universe is made out of four constituents which are fire, earth, water, and air. The visible and tangible universe is made by the combination of these four elementary bodies [32b]. When condensed, water turns into stones and earth; when dissolved or dispersed, it turns into wind and air; and when ignited, it turns into fire. Fire when condensed and extinguished, turns back to the form of air, and air coalescing and thickening turning into cloud and mist [49c].

Plato associates these constituents to the regular solids. Earth is assigned to the cube, fire to the tetrahedron, air to the octahedron, and water to the icosahedron [55d]. The fifth regular solid, the dodecahedron, receives no association to an elementary constituent but Plato identified it with the universe as a whole [55c]. It seems that the association to the regular solids is used to explain how the four elementary bodies transforms and combine among themselves to form other bodies. This is carried out by considering how a regular solid can be separated or combined to form other solids.

After introducing the four elements, the stuff of which the bodies are made of, Plato discusses the properties of bodies. The violent and sharp actions of fire are consequences of the sharpness of the angles of the tetrahedron particles and their swiftness. These actions produces in our bodies the affection that is called hot [62a]. The resistance and shivering of a body when being unnaturally compressed as well as what causes it, is termed cold [62b].

Hard is whatever displaces a part of a body and soft is whatever is displaced by a part of a body [62b]. The form composed of quadrangles, represented by the cube particles, is the least susceptible to displacement because its bases are very firm [62c]. When compacted they are particularly resistant to being displaced. Hardness combined with irregularity gives roughness and smoothness is the result of uniformity and density.

The structure of the universe is explained in Timaeus as follows. The sun, the moon and the five planets exist to show the generation of time [38c]. They revolve in seven orbits, some in a larger and some in a lesser orbit [38d]. Those with a lesser orbit revolves faster and those with a larger orbit revolves slower. The moon is set in orbit around the earth in the first circle, and the sun in the second circle above the first. The planets Mercury and Venus are also set in circles and run with a speed close to that of the sun. The small difference in speeds makes that they sometimes they overtake the sun, sometimes they are overtaken by the sun.

There is a tradition that the use of circular motions in astronomy was a suggestion advanced by Plato. In fact, Plato set for students of astronomy the task of finding out the uniform and ordered motions that could explain the apparent movements of the planets [13, 40]. This has been interpreted as if the astronomers have to explain the apparent motion, both the progressive and regressive motions, through perfect circular motions or combinations of them [40]. In any case, the circular motions dominated the theories of astronomy from Eudoxus, who was a contemporary of Plato, passing through Ptolemy in the second century AD, until around 1600 when Kepler suggested an elliptic motion for Venus.

4. Aristotle

All men by nature desire to know

Aristotle [41, 42] lived in the fourth century BC in the ancient Greece and wrote a great number of works on philosophy and other areas of knowledge. Only part of his writings reached the modern times. The standard edition of the Greek texts of his surviving works was published in 1831 [43]. The edition recognized as the standard English version was published between 1912 and 1930, and revised in 1984 [44]. We will refer to the passages of the standard Greek edition by the notation [*pcl*], where *p* is the page number, *c* is the column label, and *l* is the line number.

The surviving works contained in the standard edition comprise 46 books on the subjects of logic, physics, metaphysics, ethics, politics, rhetoric, and poetics. The books on logic are called collectively Organon. The titles of three of these books are Categories, Prior Analytics and Posterior Analytics. The titles of three books on physics are Physics, On the Heavens, and Meteorology. Here the term physics does not have the modern meaning of the science of physics, but stands for nature or related to nature. Metaphysics is the title of one of the Aristotle books. This title was not given by him but by a later editor, and means 'what comes after physics' [44]. Nonetheless, it came to mean the subject described and practiced by Aristotle in this book [44].

4.1. Structure of knowledge

The subjects of the Aristotle works that interest us here are those related to knowledge. In the first chapter of the first book of Metaphysics we find the following statements concerning knowledge: "All men by nature desire to know" [980a22] and "wisdom is knowledge about certain causes and principles" [982a2]. One of the Greek words for knowledge is *epistēmē* from which is derived the word epistemology. In the Latin translations of Metaphysics, the Greek *epistēmē* is rendered *scientia* from which comes the word science. The common meaning of the word science certainly coincides with the Greek *epistēmē* used by Aristotle since it means knowledge. However, the specific meaning of science that we use today, which involves theory and experimentation, is absent in that used by Aristotle.

In his works of logic, Aristotle presents two species of reasoning and argumentation [42]. One of them is demonstration which is the main subject of the Posterior Analytics, and the other is dialectic argument [42]. The form of reasoning called syllogism is discussed in Prior Analytics. The structure of the Aristotle science is discussed in the Posterior Analytics. It corresponds to a structure consisting of a sequence of explanations which are demonstrations and proofs carried out by deductive reasoning from primary truths (Greek *axiōmata*), which are the propositions assumed to be truth without the need of demonstration, or considered to be self-evident. He says: "By first principles in each subject matter I mean those truth of which it is not possible to prove" [76a31]. Aristotle distinguishes propositions of the general kind from those specific to a certain branch of science [76a38].

A deductive structure consisting of a set of propositions that are derived from first principles was in fact employed by Euclid in his treatise on geometry [45]. He also distinguishes the general fundamental propositions, or common notions, translated as axioms, from the specific fundamental propositions, translated as postulates. Euclid lived in Alexandria around the turn of the fourth to the third century BC, and therefore after Aristotle. The deductive scheme that he used fits the deductive structure laid down by Aristotle [45] which indicates that he might have been influenced by Aristotle methodological ideas.

The structure of science laid down by Aristotle, containing the deductive reasoning as one of its main features, is similar to that of the modern meaning of science if we drop the relationship to experimentation, and it resembles the abstract framework of a scientific theory explained in the Introduction. Being so, we would expect him to use this structure in the study of the specific sciences, as Euclid later did with geometry. However, in his studies of the specific sciences, the deductive reasoning plays a less important role, which is odd given the importance attached to it by Aristotle [18, 42]. The structure of the theories of the specific disciplines is effectively a collection of propositions connected by more or less informal arguments lacking the general deductive reasonings as well as the syllogisms [42].

4.2. Substance, causation, and change

The key concept of Aristotle metaphysics is that of substance. The term *substance* translates the Greek *ousia* used by Aristotle which literally means 'being' [46]. Substance is the answer to the question [1028a13]: what is it to be a thing? It is the essence [1031a15], the ultimate substratum which is not a predicate of anything else [1017b23]. If one removes all the predicates what remains is the substance. Aristotle gives a list of ten categories, the first of which is the substance and the other are predicates. The list, along with examples of each categories, is as follows [1b27]:

substance (man, horse),
quantity (four-foot, five-foot),
quality (white, grammatical),
relation (double, half, larger),
place (in the Lyceum, in the market-place),
time (yesterday, last year),
position (is-lying, is-sitting),
state (has-shoes-on, has-armor-on),
action (cutting, burning),
affection (being-cut, being-burned).

Another important concept is that or causation, developed in Physics. He considers four types of causes or four factors [198a24,983a25]:

form,
matter,
moving cause,
final cause, or teleology.

These four factors can be understood by the example of the making of a table [46]. To produce a table we need the material, for instance, wood, which is the matter factor. We need to know the shape of a table, which is the form factor. The table is made by someone, the carpenter, who represents the moving cause. The final cause is the purpose for which the table is made, for instance, a place to eat at.

In the above example, it is clear that the final cause is the result of the conscious deliberation of the craftsman who is external to the object itself. But one does not expect such a separation nor a conscious purpose in nature, that is, nature does not deliberate. In spite of that, Aristotle concedes that the final cause, or purpose, is to be found in nature itself [199b26]. Natural objects have their purposes within themselves [46]. To illustrate that the purpose can be in nature itself, Aristotle gives the example of a doctor doctoring himself [199b30].

The concept of change is essential in Aristotle reasonings. The two aspects related to change are:

> potentiality, actuality.

A seed is not actually a tree but it is potentially a tree. A piece of marble is potentially a sculpture, and a piece of would is potentially a table. In these examples, the tree, the sculpture, and the table may be said to come into being. They do not come into being from nothing, but from something, the seed, the marble, and the wood [46].

Change is a main concept in Aristotle theory of the structure of matter and its transformations, which is based on the four elements:

> fire, earth, water, air.

These elements are not created from nothing but are transformed into one another [305a33] as occurs to water in the boiling process when it is being transformed into air (vapor). In the *Meteorology* [339a36], Aristotle says that the four elements "come to be from one another, and each of them exists potentially in each of the others, as is the case with all things that have a common substrate into which they ultimately resolve".

Change is also the key concept related to the motion of bodies and was used by Aristotle to explain why the motion of a body is towards its own place. The reasoning used by Aristotle to show why fire moves upwards and earth moves downwards is similar to explaining what happens when a sick person is no longer sick. When that happens the person becomes sane and not something else like white. That is, the healable attains health and not whiteness [310b16].

4.3. Place, void, and time

The knowledge and understanding about a subject is attained by acquaintance with its principles, causes and elements. This is the first task in relation to the science of nature [184a10]. Nature includes motion and change, and to understand nature we should understand what motion is [200b12]. Motion is something that is continuous in the sense that it is infinitely divisible. In addition to continuity, the other conditions of motion are place, void, and time [200b20].

Place is a basic concept because things that exist in nature are somewhere [208a30]. It is the space occupied by a body, and motion is change of place. Each elementary natural body is carried to its own place, if it is not hindered. The proper place is up for the element fire and light bodies, and down for the element earth and heavy bodies. A body is bounded by the three dimensions of place which are length, breadth, and depth [209a5]. But place cannot be body otherwise there would be two bodies in the same place. It should be noted that Aristotle considered that place is created when something grows and is destroyed when, for instance, water is produced from air (vapor).

For Aristotle, void is place deprived of body, a place with nothing in it. He believed in the impossibility of a void what is equivalent to say that there is no place deprived of body. He argued that in the void no natural motion could be possible, that is, the elementary bodies could not find the ways to their natural place [214b12] because in the void things could indistinctly move in any direction [215a23].

Another argument against the existence of void is that in the void the velocity of a body would increase without limits [216a10]. Aristotle assumes that [215b1]:

> the times it takes for a body to travel a certain distance through a medium is proportional to the resistance of the medium.

A medium which is not easily divided and thus more dense is more resistant.

If one medium is the void an the other is the plenum, this ratio vanishes and the velocity in the void would be infinite, or equivalently the motion would be instantaneous. As this is impossible, the void could not exist.

Time has to do with change and does not exist without change, but it is not change or motion. When the state of our minds do not change we do not think that time has elapsed [218b21]. We apprehend time when we observe a body in motion [219a23]. It is measured by the motion and motion is measured by the time because they are related to each other [220b15].

4.4. Motion

The fundamental principle concerning motion is summarized by Aristotle as follows: "Every thing that is in motion must be moved by something" [241b34], that is, the motion of a body is caused by another body, the mover. Aristotle establishes the relation [249b30]: If the motive power of the mover results in the motion of a mobile a certain distance in a given time, then in the same time the same motive power of the mover will move half the mobile twice the distance, and in half the time it will move half the mobile the same distance. This relation can be summarized as follows:

> the times it takes for a body to travel a certain distance is inversely proportional to the motive power of the mover.

If we consider a larger body, the time will be proportionally larger considering the same motive power and the same distance.

There are four kinds of locomotion caused by the mover [243a17]: pulling, pushing, carrying, and twirling. The other motions reduces to these locomotions. Aristotle argues that "in all locomotion there is nothing between moved and mover" [244a5], which means to say that the motion occurs by the contact between the mover and the moved body.

A mover is necessary to set in motion inanimate things. An animal, on the other hand moves itself [252b23], that is, motion is produced by the animal itself, and not without. Some motions are natural and others are violent or unnatural [254b13]. The motion of bodies that moves themselves, such as the animals, is always natural. The motion of inanimate bodies can be natural or unnatural. The downward motion of the element earth and the upward motion of fire are natural whereas the upward motion of the element earth and downward motion of fire are unnatural. Similarly the upward motion of light bodies and downward motion of heavy bodies are unnatural

A body in motion needs a mover which in turn needs another mover and so on [256a6]. A stone is moved by a stick, which is moved by the hand, which is moved by the man, which does not need a mover because he is its own mover. The series terminate in someting that moves itself. Aristotle argues that all series terminates in one mover which is eternal and is the primer unmoved mover, and the principle of motion of everything else [258b14]. We illustrate this as follows:

> prime mover/mover/.../mover/mobile

The motion of things is either circular, rectilinear or a combination of both [261b29]. If the motion of a thing is rectilinear and finite, it is not continuous because the thing should turn back to return to the original place, transforming a motion in one direction into a motion in the opposite direction. On the other hand, a circular motion can be continuous because here there is no need to turn back to return to the original place. The circular motion is the only eternal motion because in the other kinds of motion the rest must occur [265a25].

4.5. Motion of a projectile

Aristotle discusses a difficulty related to the motion of thrown objects in the air or in the water [266b27]. After the release, the projectile continues to move, although there is no longer the agent of the movement. As any motion needs a mover, the motion of the projectile could not take place because after the throw there is no mover to move the project. Aristotle circumvents this problem by supposing that the mover gives the power to the air or to the water to convey the motion to the projectile [266b27-267a20].

An equivalent explanation was given by Aristotle when he argued against the existence of void [215a14-18]. He stated that the air that has been displaced by the projectile pushes it forward by a reciprocal replacement, which translates the Greek *antiperistasis*, of the air by the projectile. That is, the air turns around and pushes the projectile from behind. As the presence of the air is necessary to push the projectile forward, motion would be impossible in the void.

4.6. The heavens

The simple movements are either circular or straight, and all movements, all locomotions are either one of these or a combination of these [268b16]. Bodies are compounded by simple bodies, such as fire and earth, which possess a principle of movement [268b27]. There is one sort of movement for each of the simple bodies. The natural motion of fire is upward, the natural motion of earth and water is downward. Those that naturally move upwards and downwards are respectively the lighter and the heavier. There must be some simple bodies whose natural motion is circular. The circularity prevents them of having lightness or heaviness [269b30]. These bodies are ungenerated and indestructible because the circular motion does not have a contrary motion and being so it cannot be changed [270a34]. The substance of these bodies is not that of earth, fire, air, or water, and is called aether (Greek *aither*) which means running forever through eternity of time [270b22].

Aristotle asks whether there exists infinite bodies. He first argues that a body that moves in a circle is not infinity or endless. For bodies that moves downward, the question reduces to ask whether there exists a body with infinite weight. Two answer this question he considers the downward motion of a body. He assumes that [273b30].

> the time it takes for a body to travel a certain distance is inversely proportional to its weight.

If the weight is infinite, this time would vanish and the motion would be instantaneous, which is an impossibility. Thus a body with infinite weight is impossible. Aristotle adds that the same reasoning can be used to show that a body with infinite lightness is also impossible.

Aristotle argues that the universe is finite that cannot be more than one heaven [276b17], and that the heaven is eternal and exempt from decay and generation [277b27,279b4]. There are several meanings of heaven

[278b10], one of them being the extreme sphere containing the moon, the sun, and some of the stars. The other is the substance of this sphere, and a third refers to all bodies included in this sphere. The shape of the heavens is spherical which is that appropriate for its substance [286b10], and its motion is regular [288a14].

The stars are not self-moved, but move with the circle to which they are attached [289b32]. The larger circles move faster than the smaller circles and the revolution of the larger ones takes the same time as that of the smaller ones. From this it follows that the heavens do not break down maintaining its integrity. The stars are spherical but do not have motion of their own. The fixed stars twinkle but not the planets. Aristotle attributes the twinkling of the fixed stars to their great distance which makes the visual rays to tremble producing an apparent motion of the object of vision[1] [290a20].

The speed of the several stars depend on their distances. The revolution of the outermost sphere is a simple movement and the swiftest and so are those of the stars attached to it, the fixed stars. The motion of the other bodies are composite and slower. Each of these bodies moves in its own circle and completes a revolution in a time that is greater the closer it is from the fixed stars [291b5]. These bodies are the sun, the moon and the planets.

The crescent and the gibbous figure of the moon indicates that it has a spherical shape [291b15]. A further evidence is given by the crescent shape of the eclipse of the sun. As one of the heavenly bodies, the moon, is proved to be spherical so must be the other bodies of the heavens.

4.7. The earth

Regarding the position of the earth and the question whether it moves or is at rest, Aristotle places it at the center and at rest, but says that some people have distinct opinions [293a15]. Plato in the TIMAEUS, says Aristotle, also places the earth at the center but it does not remain immobile but rotates about the axis of the whole heavens. As to the shape of the earth, he supports its spherical shape but says that this is not the sole opinion [293b33]. Some say that it is flat and has the shape of a drum and others say that the earth rests upon water, a theory due to Thales. Anaximenes, Anaxagoras, and Democritus say it is flat on the account of its immobility, like the water in a clepsydra.

Aristotle observes that the sphere of the earth is not of great size because a small change in position along the north-south direction causes a perceptible alteration of the horizon and the change of the stars that are overhead [297b33]. He states that the size of the earth circumference has been estimated by mathematicians who arrived at the value of four hundred thousand stades.[2] Aristotle expressed the view that the spherical shape of the earth lead some people to conceive a continuity between the region of the pillars of Hercules (strait of Gibraltar) and India, and concludes that the ocean is one.[3]

The natural things are composed by the simple bodies or elementary bodies [298a30]. They are endowed with weight and lightness [300a17] and have a natural movement which is not constrained or contrary to its nature [301a20]. Heavy and light bodies are characterized by their motion in relation to the center. The absolute light bodies move upward and the absolute heavy bodies move downward or to the center [308a29]. Fire is always light and moves upwards and earth moves downwards [308b13].

As to the other elements, water and air, none of them are absolutely heavy or absolutely light [311b8]. Both are lighter than earth and heavier than fire as they rise to the surface of earth and sinks to the bottom of fire. When one compares water and air, we see that air is lighter than water since it rises to the surface of the latter, and water is heavier than air since it sinks to the bottom of air. In Aristotle conception, they are composed of *both* heaviness and lightness in different proportion. Heaviness is related to the presence of plenum and lightness to the void. Water is heavier than air because the proportion of heaviness in it is higher than that of lightness. Of the four elements, fire has only lightness whereas earth has only heaviness.

4.8. The four elements and four qualities

Aristotle states that knowledge depends on what is primary. Concerning the constitution of bodies, the elements are the primary constituents of bodies. An element is a body which is present potentially or actually in other bodies, into which all other bodies can be resolved, but not itself resolved in other bodies [302a10]. The elements cannot be generated from which is not an element. The only possibility is that they are generated from one another, or that they are transformed into one another [305a33]. Aristotle argues that the number of elements is finite but cannot be just one. As did Empedocles and then Plato, he assumes that they are: fire, earth, water, and air.

The Aristotle theory of qualities is based on the assumption that they exist in pairs of contrarieties such as heat-cold, dry-moist, heavy-light, hard-soft, brittle-viscous, rough-smooth, and coarse-fine [329b20]. From the first two pairs one derives the other pairs. The coarse and the fine are derived from the dry and the moist, respectively. The brittle is that which is completely dry and viscous is something which is moist to a certain

[1] In fact, the great distance makes a star to become a point like source of light which is easily disturbed by the earth atmosphere.

[2] This value is much larger than the present value, but considering that it is the first recorded estimate of the circumference of the earth, it is a creditable achievement [46].

[3] Based on this passage, Roger Bacon wrote that the distance between Europe and Asia was small. This was quoted in a book of the fifteenth century, which in turn was read by Columbus [47].

degree. Hard is that which is solidity and thus dry. The soft derives from the moist. The first two pairs, heat-cold and dry-moist admit no further reduction for each one of these four qualities are essentially distinct [330a26].

The four elementary qualities, heat, cold, dry, moist can be combined into four pairs: hot-dry, dry-cold, cold-moist, and moist-hot. These four pairs are associated, respectively, to the four elementary bodies: fire, earth, water, and air. For fire is hot and dry, earth is dry and cold, water is cold and moist, and air, being a sort of vapor, is moist and hot [330b1]. Fire is contrary to water and air is contrary to earth because they consist of contrary qualities.

The change of one element into another occurs when one quality is replaced by its opposite while the other remains invariant. Water changes into air (vapor) in the boiling process which is interpreted as the change from the cold to hot, the wet remaining invariant. The opposite occurs when the air (vapor) changes into water in the condensation. Aristotle does not explain how a quality is transformed into the opposite quality [46]. He does not explain either the distinction between air and hot water as both are hot and wet, or between cold air and water as both are are cold and wet [46].

5. Galen

The Aristotle theory of the four elements and the four qualities was used as the physical basis of the physiology of Galen, the Greek physician who lived in the second century and spent part of his life in Rome [19, 48]. He wrote a great number of treatises mainly on medicine and biology, but also on philosophy. He claimed that the four qualities were first propounded by Hippocrates, the Greek physician who lived in the fifth and fourth centuries BC [19, 48].

Galen pursued a more precise characterization of the primary qualities, which he called principles and not elements. He distinguishes between a proper and an acquired quality, that is, between bodies that have naturally a certain quality from those that have acquired it accidentally. The second type is easily recognized as it corresponds to an acquired property which is quickly lost and the body returns to its original condition. Among the first, he distinguishes four degrees for each quality [19, 48] which are explained in his work on simple drugs [49].

The four degrees of heat are as follows. The first degree is imperceptible to the senses but is recognized by reason. The second degree is the mildest heat perceptible by touch. The third degree is the intense heat without burning. The fourth degree corresponds to the heat that actually burns [48, 49]. The four degrees of coldness are as follows. The first is imperceptible and needs the aid of the reason to be recognized. The second is that which is sensible. The third is a strong coldness. The fourth is the strongest and is distinguished from the third in that it induces death [49]. Similarly, the four degrees can be extended to other qualities such as wetness and dryness.

The Galen gradation theory is clearly an attempt to describe the intensity of our sensations. Our sensations tell us, for example, that there is no absolute sensation of heat. A body is hot in relation to another, a perception that leads to a gradation of the heat sensation. Depending on the type of quality we are able to distinguish the various degrees of its intensity. Galen assumes that this can be done through four degrees, as explained above. It is interesting to notice that his theory leads to a gradation of seven degrees for a pair of opposite qualities as each has four but one of them is neutral and the two neutral degrees of the two qualities can be identified as a single degree

6. Philoponus

We recall that Aristotle found it difficult to explain the continuing motion of a projectile once it was thrown. According to his theory, the motion of a body needs a mover, which in this case is the thrower of the projectile. But after the projectile has been thrown the mover no longer exists. To overcome this problem Aristotle assumed that the mover gives the air the power to transmit motion to the projectile. A distinct solution to this problem was given by John Philoponus, who lived in the sixth century and taught in Alexandria [21]. He wrote a large number of works, some of them being commentaries on the writings of Aristotle. His theory of projectile motion is contained in his commentaries on the *Physics* of Aristotle [13].

Philoponus presents first the Aristotle explanation by antiperistasis as follows. The air that has been pushed forward by the projectile moves back to the rear, takes the place of the project, and pushes the projectile on. Philoponus finds it difficult to understand how it is possible for the air pushed by the project to turn around instead of moving forward. In addition it is hard to imagine that the projectile will be moved by the air behind it. It is not the air that produces the motion of the projectile, he says.

Philoponus assumes that [13] "some incorporeal motive force is imparted by the projector to the projectile, and that the air set in motion contributes either nothing at all or else very little to this motion of the projectile". The motion of the projectile is caused by a motive force impressed in the body itself and not in the medium [17]. This impressed force decreases by the resistance of the air or by the weight of the body [17].

The falling of bodies is also discussed by Philoponus [13]. According to Aristotle, the ratio of the times required to travel a certain distance by bodies of different weights is equal to the inverse ratio of their weights. After stating that this in incorrect Philoponus presents his theory. “If two bodies of different weights fall from the same height, the ratio of the fall times does not depend on the ratio of their weights, but that the difference of the times is very small”. If for instance one body is twice the other, the difference in time is negligible.

When comparing the motion of a body in a medium and in the void, an additional time is required due to the resistance of the medium. The thinner the medium through which the motion takes place, the less will be the additional time. Philoponus proposes that “the additional time is proportional to the density of the medium”. This proposition is distinct from the Aristotle theory which states that it is the time traveled that is proportional to the density of the medium.

7. Ibn Sina

Ibn Sina, or Avicenna, lived between 980 and 1037 in the region that is now part of Uzbekistan, Turkmenistan, and Iran [50, 51]. His major philosophical work called The Healing consists of a collection of books on logic, natural sciences, mathematical sciences (geometry, astronomy, arithmetic, and music), and metaphysics. The title refers to healing the ignorance of mind. A smaller book on the same subjects, called The Book of Science [52], was written by Avicenna in Persian, his mother tongue.

We present some of his thoughts contained in the metaphysics of The Book of Science [52]. Everything that is not accident but is the essential reality of a thing is its substance. A body is matter and form united by the substance. The accidents are of two types. The first type comprises quantity and quality and the second type includes the relationship between things, the place of a thing, the time when it is found, its arrangement, and its action. The cause of an accident is in the body itself or come from outside the body. An example of the first kind is the fall of a stone which is a consequence of its weight. An example of the second type is the heating of water which comes to it from the outside.

There are two types of powers in a body. One of them is the active power which occurs for instance when the water is actually boiling. The second type of power is the passive when one thing is the receptacle of another. For instance a piece of wax can receive a shape by the modeler. In other terms, the wax is potentially a model. The bodies are classified as simple or compound by simple bodies. The second type may have a property which is not present in the simple bodies separately but exists in them as a principle.

We examine now the part of The Book of Science concerning with the science of nature, which is related to matter and motion. Everything that is in motion, moves by itself or because something sets it in motion. The first type is the natural motion such as the downfall of a stone, or the hot water that cools spontaneously. The second type is the forced or violent motion such as motion of an arrow by the bow, or the fire that heats the water.

The natural motion are either circular or rectilinear. The rectilinear motion can be upward, like those of fire and air, and is caused by lightness, or downward, like those of water and earth, and is caused by heaviness. Fire rises to the extreme limit and air rises below that limit. Earth descends to the extreme limit and water descends above this limit.

Avicenna believes that the void cannot exist. One of his reasonings against its existence is related to the functioning of a siphon. A tube with the top closed is placed inside water and then raised vertically out of the water so that the bottom remains inside water. The water inside the tube will not run off the tube and the tube will not become empty because the water cannot be separated unless it is replaced by something. The same happens to a siphon. The water keeps flowing from one extremity to the other of the siphon. The column of water does not break which means that the void is not produced.

Next we examine the motion of a projectile as discussed by Avicenna in the part of The Healing dealing with natural science [53]. The explanation given by Avicenna to the projectile motion is similar to that of Philoponus. It is based on the concept of the Arabic *mayl* [50, 53], translated as *inclination* in the sense of ‘propensity’ or ‘tendency’ and not of ‘bending’ or ‘tilting’. According to Avicenna, the projectile receives from the thrower an inclination which allows the unnatural motion of the projectile [50].

Avicenna distinguishes three types of inclination: psychic, natural and violent. The violent inclination is the cause of the violent or unnatural motion. The natural inclination is the cause of natural motion. The heaviness is the inclination to downward natural motion whereas the lightness is the inclination to the upward natural motion.

Although criticizing it, Avicenna theory is very similar to that of Philoponus. The projectile acquires an inclination from the thrower. Inclination is what one perceives when one tries forcibly to bring to rest something whose motion is forced or natural. This statement by Avicenna tell us that the inclination is something that lasts even when the motion is decreased by the friction with the air. It differs from the Philoponus impressed force, which decreases continuously due to friction with the air.

Avicenna assumed that only one type of inclination could reside in a body in a given time [17]. Thus the forward motion of a projectile is related to the violent inclination. At a certain time this inclination is destroyed and replaced by the natural inclination, or heaviness, which would produce the downward fall. Between the two stages the projectile is brought to an instantaneous rest.

8. Buridan

We have seen that the Aristotle explanation of the projectile motion was rejected by Philoponus who proposed that the projectile is maintained in motion by the action of a motive force impressed by the thrower. This idea was developed further by Buridan, who called *impetus* the impressed motive force. Jean Buridan lived in the fourteenth century and taught at the University of Paris [17, 54]. Most of his works consist of commentaries on Aristotle written in the form of questions [54].

His impetus theory of projectile motion is presented in question 12 of book 8 of his commentaries on the physics of Aristotle [17]. Buridan presents the antiperistasis theory of Aristotle as follows. The projectile leaves the place where it was, which is quickly occupied by the air, as nature does not permit the void. This air pocket impinges upon the projectile propelling it forward. One of the counter-examples given by Buridan is a boat which is drawn swiftly in the river. After the drawing has ceased, the boat keeps moving for a while and someone on the boat would not feel any air from behind pushing the boat.

At the moment of the throw, something is impressed in the projectile which is the motive force of the projectile. The mover, which is here the thrower, in moving the projectile impresses in it an *impetus* or a motive force, which acts in the forward direction. But the impetus does not remain the same and decreases continuously on account of the resisting air. Buridan also ascribe to the gravity the decrease of impetus because it declines the projectile in a direction contrary to that induced by the impetus.

The faster the motor moves the projectile, the stronger will be the impetus, and the more matter has the projectile, the more intense will be the impetus. Of the two bodies that differ only by density, the denser will receive the greater impetus. Buridan makes an interesting analogy by stating that iron receive more hotness than wood or water of the same quantity.

The impetus is also responsible to the continuous increase in the velocity of a falling body. Initially, the motion is slow because only the gravity moves it. But in moving, the gravity impresses in the body an impetus, and the motion becomes faster, which in turn increases the impetus, and so on. Thus the motion becomes continuously faster.

In his final comments, Buridan points out that impetus is not motion but is understood as a quality naturally present in a body in which it was impressed. He gives the analogy with that quality impressed in iron by a magnet which makes the iron moves to the magnet.

In question 12 of book 2 of his commentaries on the heavens of Aristotle [17], Buridan discusses again the fall of a heavy body. During the fall the motion does not remain equally fast but becomes continuously faster. From these supposition, that the motion increases, one concludes that there is another moving force in addition to gravity, which remains the same during the fall. The body acquires motion by a certain impetus which does not remain the same but increases with the increasing motion.

9. Before Galileo

9.1. Motion of bodies

The theories of motion from the thirteenth to the seventeenth century were dominated by the thoughts of Aristotle on the subject. The development did not occur without criticism on Aristotle, which eventually led to the overthrow of the whole physics of Aristotle [14]. The two problems on the subject that were mostly discussed were the persistence of projectile motion and the acceleration of bodies in free fall [17].

Concerning the free fall of bodies, Benedetti expressed his opposition to Aristotle in a publication of 1554 [17]. He held that two bodies of different weights and of the same species fall from the same height at equal times. The same opinion was expressed by Galileo in his work on motion, which he wrote before 1592 but which was not published during his lifetime [55]. As Benedetti, he speaks of bodies of the same material, such as lead or wood.

The opinion of Benedetti and Galileo on the fall of bodies did not concern the cause of fall which remained the same as that held by Aristotle. Nor did it concerned the type of motion that occurs during the fall. This second problem was later solved by Galileo by stating that a freely falling body follows a motion in which velocity increases linearly with time. But before Galileo, it was already clear that the velocity increases during the fall as stated by Jordanus, Buridan, and Oresme [17].

Albert of Saxony held that the velocity is proportional to both distance and time [17]. This confusion was held by others including by Galileo before 1604, and, in our opinion, it arouse because velocity was not a well defined concept except in a uniform motion. Thus any proposition involving velocity in non uniform motion becomes meaningless, causing obscurities. The proposition that velocity is proportional to time, which seems to be a fair statement, is in fact meaningless without a precise definition of velocity.

Concerning the motion of projectiles, Buridan rejected the peristasis theory and explained the persistence of motion of a projectile by his impetus theory. Leonardo da Vinci used the impetus concept to develop a theory of projectile motion that consisted of three stages [1]. The first is a pure violent motion dominated by the impetus, the last is the natural downward motion, and the intermediate is a composition of these two. Tartaglia, in his work on mechanics published in 1537, improved the theory by proposing that in the first stage the motion is rectilinear, the last is vertical and the intermediate is an arc of circumference joining the first and last stages [1].

9.2. Abhorrence of a vacuum

The principle that nature abhors a vacuum emerged in the thirteenth century and became a subject of debate in natural philosophy until the seventeenth century [56]. Within this period, vacuum was understood in the sense given to it by Aristotle as a place deprived of body, a place with nothing in it. In spite of such a positive definition Aristotle believed that it did not exist [56], a belief that became expressed as the abhorrence of a vacuum. It should be noted that Aristotle used the Greek term *kenos* which means 'void'. This term was translated into Latin as *vacuum* which in turn originated the word *vacuum* and the Italian *vacuo* used by Galileo.

Two types of vacuum were distinguished: the interstitial and the separate or extended [56]. The interstitial vacuum was associated to condensation and rarefaction. Nicholas of Autrecourt, for instance, believed that the interstitial vacuum could provide an explanation of rare and dense, but that the separate vacuum was impossible [56]. Several experiments were used to illustrate the abhorrence of a separate vacuum [56]. In one experiment, disseminated by Averroes, a burning candle stands in a shallow dish of water and a glass vessel is inverted in the surface of water such that the candle becomes inside the inverted vessel. The water rises inside the vessel to replace the air destroyed by flame and thus preventing the formation of a vacuum [56].

Another experiment that was discussed by Averroes is the raising of water in a reed when it is placed in water and the air is sucked out. Buridan declares that when the air in the reed is drawn up, the liquid although heavy follows the air so as to prevent the formation of vacuum. William of Moerbeke describes how the water is drawn up in siphons and the functioning of cupping-glasses. Marsilius of Inghen describes the action of a siphon by stating that the water rises through the small arm because otherwise it would not prevent a vacuum [56].

Another type of devices mentioned in the discussion of vacuum was the bellows. Buridan argued that we cannot separate the surfaces of a bellow after the air is expelled and the surfaces are in contact because if we could do that a vacuum would be created. Abelard of Bath described a device also use to show the abhorrence of a vacuum. It is a metal vessel of the shape of a spherical bottle with a narrow neck with tiny holes at the bottom. The vessel is submerged until it becomes full of water. After lifting the vessel with the neck orifice stopped up by the thumb, one observes that the water does not fall through the tiny holes [56].

10. Galileo

10.1. Motion of bodies

The motion of bodies is treated by Galileo in the Two New Sciences, published in 1638 [57, 58]. In this book, he dealt with two main topics. One is the cohesion and resistance of materials and the other is the motion of bodies under gravity. The Galileo theory of motion described in this treatise is kinematic, leaving aside the causes of the movement. He starts by the definition of two types of simple motion. The first is the uniform motion defined as that in which a mobile travels equal distances in equal times. That is, the velocity is constant along this type of motion. The second type of motion is the uniformly accelerated motion in which a body acquires an equal increment in velocity during equal intervals of time. That is, the increase in velocity is proportional to the time elapsed.

Galileo demonstrates the mean velocity theorem stated as follows. The time spent by a body in a uniformly accelerated motion to travel a certain distance is equal to the time spent by the same body to travel the same distance through a uniform motion with a velocity which is the mean of the initial and the final velocities. The importance of this theorem lies in that it allows the indirect measure of velocity in uniformly accelerated motion. For instance, the final velocity of a body undergoing this type of motion, starting from rest, is equal to *twice* the ratio of the traveled distance and the time elapsed.

From the mean velocity theorem, he demonstrates that the distance traveled by a body undergoing a uniformly accelerated motion falling from rest is proportional to the square of the time elapsed. From this result it follows that the distances traveled in equal time intervals are proportional to the odd integers. Another result derived by Galileo is that the the distance traveled from rest is proportional to the square of the velocity.

Galileo proposes that the bodies in free fall moves in accordance with a uniformly accelerated motion. Considering the free fall from rest, we may write the results obtained by Galileo as follows. We denote the final velocity by v, the distance travel by s, and the time elapsed by t. Definition of uniformly accelerated motion: $v = at$. Mean velocity theorem: $v = 2s/t$. Relation between distance ant time: $s = at^2/2$. Relation between distance and final velocity: $v^2 = 2as$. We remark that Galileo stated these results in geometric language and not in algebraic language like we are doing here.

The uniform accelerated motion is also extends to the motion of bodies in inclined planes. He assumes further that the velocities acquired by a body descending planes of different inclinations are equal if the heights of the planes are equal. He then generalizes this result for the motion of bodies descending any type of curve. If we denote the height of the plane by h, this assumption is expressed as $v^2 = 2ah$.

If a certain velocity is imparted to a body which moves in a horizontal plane, this velocity is maintained as long as there is no causes of acceleration or retardation. This result is shown by Galileo by using two inclined planes. A body is released at a certain height from an inclined plane, then moves along a horizontal plane and then up the second plane. Galileo argues that the body reaches the same height which is only possible it the body moves with constant speed along the horizontal plane.

Galileo also discusses the motion of projectiles and shows that the motion of a projectile is a parabola. To this end, he argues as follows. A body moves without friction on an elevated horizontal plane with a certain velocity. It reaches the edge of the plane and then in addition to its previous uniform motion it acquires a downward tendency due to its weigh. Galileo assumes that the resulting motion is compounded by a horizontal uniform motion and a vertical uniformly accelerated motion. This is equivalent to say that the horizontal projection motion is uniform whereas the vertical projection motion is uniformly accelerated.

10.2. Definition of velocity

The development of the Galileo theory of motion depended on a fundamental change in the meaning of the concept of velocity. Before Galileo, velocity was a understood in its common meaning as the 'quickness of motion'. In his demonstration of the mean velocity theorem, Galileo implicitly advanced a definition of velocity which is equivalent to the Newton definition of velocity in rectilinear motion, that is, as the time derivative of the distance traveled by a body.

In the demonstration of the mean velocity theorem, Galileo used a right triangle to represent a uniformly accelerated motion where the basis represents the time and the height represents the velocity. In the course of the demonstration he implicitly identified the *area* of the triangle as the *distance* traveled. The explicitly recognition that the area of the triangle is the distance traveled was given later by Huygens [9]. In modern terms this means that the distance is the integral in time of the velocity from which follows that the velocity is the differential of distance with time.

Before Galileo, the mean velocity theorem was known but its meaning was not the same as that given by Galileo. One of the demonstrations was given by Oresme, who lived in the fourteenth century [17]. Oresme distinguished a quality by its intension and extension. The extension or longitude is represented by a horizontal line and the extension or latitude by a vertical line. A rectangle represents a uniform quality as the intensities are the same along the extension. A right triangle represents a nonuniform quality, such that the intensity increases uniformly with extension.

The mean theorem is demonstrated by assuming the equality of the areas of the triangle and of the rectangle with the same extensions. From this assumption it follows that the height of the rectangle is half the height of the triangle. Oresme applies the theorem to the motion of bodies by considering that velocity can be understood as a quality, the extension of which is the duration of motion. The vertical lines are the intensity of velocity and the area is called the quantity of velocity. It is not clear whether Oresme identified the quantity of velocity with the distance traveled as he did not developed further the theory.

11. The Barometric Experience

11.1. The production of vacuum

Galileo discusses the problems related to vacuum in the part of the Two New Sciences concerned with the cohesion and resistance of materials. For Galileo, there are two causes of cohesion. One of them is a kind of glue that binds the parts of the bodies and the other cause is the repugnance to the vacuum (*repugnanza al vacuo*). In liquids the latter is the only cause of cohesion, which is translated into a force that opposes or resists the pulling force that tries to separate the liquid.

The distinguishing feature of the Galileo repugnance of vacuum lies in its limitation. He reached this conclusion by observing the lifting of water in cistern by suction pumps. If the distance from the surface of the water and the suction pump is larger than eighteen cubits (*diciotto braccia*) it is not possible to raise the water.

The limitation of the repugnance to the vacuum had already been expressed by Galileo in response to a letter from Baliani, one of his correspondents [59]. In a letter to Galileo dated 27 July 1630 [60], Baliani reports his failure to carry water over a hill of a height of 70 feet using a cooper siphon. To start the operation, its two ends are closed and it is filled with water through an opening in the upper part. Then it is closed and both ends are opened. However, the siphon did not work. The water went down both arms of the siphon. If only the end of the smaller arm is opened, the water does not come out completely, stopping halfway up the smaller arm. In the reply to Baliani dated 6 August 1630 [60], Galileo says that the failure of the enterprise is linked to a problem that he had already examined for some time, which is the impossibility of raising water by suction beyond a certain height. Then he presents the explanation found in the Two New Sciences.

An experiment to produce the void was carried out by Berti in Rome around 1641 [61, 62]. The experiment was described by four accounts. One account was given by Magiotti in a letter to Mersenne dated 12 March 1648 [61]. Another account written by Maignan is contained in his book on natural philosophy published in 1653 [61–63], where an illustration of the apparatus used by Berti, shown in Figure 1, can be found.

The Berti experiment is described by Maignan as follows. A long pipe of lead AB was erected on the wall of his house. The lower end B had a brass tap and was inside a container filled with water. The upper end A joined a large glass flask which was connected to a tube whose end G had a tap and was inside another container. The whole apparatus functions like a siphon with a small arm GA and a large arm AB. With the two taps A and G

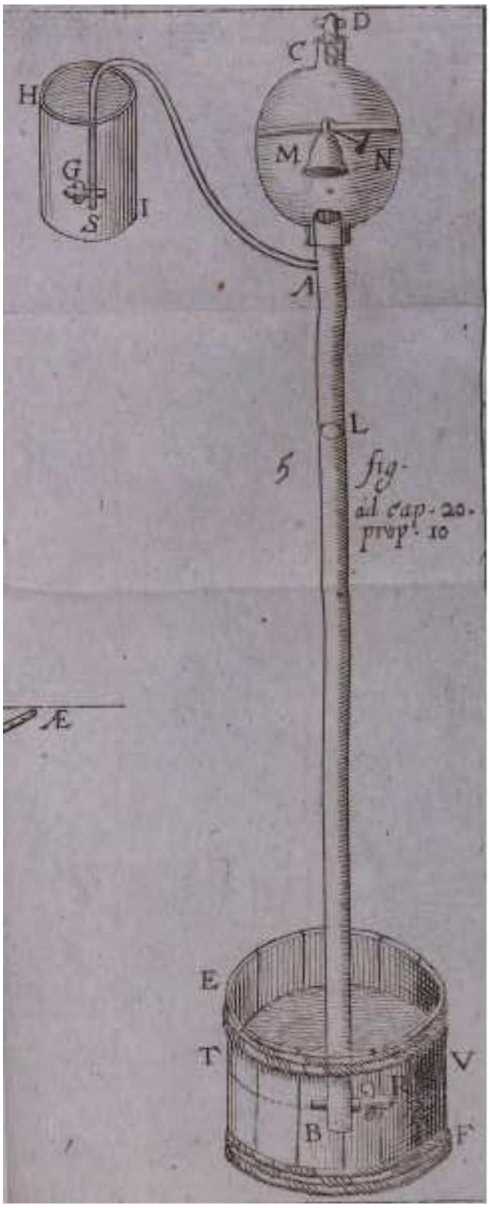

Figure 1: Illustration of the experiment carried out by Berti contained in the book by Maignan [63].

closed, the whole siphon was filled with water through an aperture C at the top of the glass flask. After closing C, the bottom tap B was opened and water flowed out of the pipe into the container. But not all the water flowed out. Part of the water remained in the pipe. The column of water was found to measure eighteen cubits, the same as that predicted by Galileo.

Magiotti, at the end of his account, states that he wrote to Torricelli reporting the Berti experiment and believing that the liquid column would be lower if one uses a denser liquid such as sea water. It so happened that Torricelli ended up devising an experiment with a denser liquid, the mercury. The actual experiment was set up and carried out by Viviani [61, 62] and was reported by Torricelli in a letter to Ricci dated 11 June 1644 [64, 65].

A long tube, two cubits long and sealed at one end, was completely filled with mercury. Closing the tube with a finger, it was overturned in a vessel containing mercury and placed in an upright position. Withdrawing the finger, it was found that some of the mercury in the tube had descended into the vessel leaving an empty space at the top, and that the length of the column of mercury in the tube had become one cubit and a quarter and one inch (*un braccio, e un quarto, e un dito di più*). To show that a vacuum had been produced in the upper part, water was placed in the vessel, which formed a layer over the mercury, and the tube was slowly lifted. When the mouth of the tube hit the water, suddenly, all the mercury in the tube descended and the water rose through the tube, filling the tube completely.

11.2. The weight of air

Noi viviamo sommersi
nel fondo d'un pelago d'aria elementare
Torricelli, 1644

In his letter to Ricci, Torricelli explains that it is not the abhorrence of the vacuum which is present in the upper part of the tube that prevents the mercury column from falling, but that it is supported by the weight of the air acting on the surface of the container. Torricelli explains that "We live submerged at the bottom of an ocean of elementary air, which is known by incontestable experience to have weight, that the heaviest part near the surface of the earth weights about one four-hundredth as much as water".

Explanation similar to that of Torricelli, based on the weight of the air, had been considered by others. Beeckmann knew already in 1615 that the lifting of water by a suction pump is limited, although he did not indicate the limiting value [61]. He assumes that pulling the piston will create a vacuum under it and the weight of the atmospheric air will push the water upwards [61].

An explanation concerning the maximum height of a column of water which can be attained by suction was given by Baliani in a letter to Galileo dated 24 October 1630 [60]. In this letter, he clarifies that he holds the opinion that the vacuum has a real existence although it is difficult to produce it. He says that he was convinced of this when he realized that air has weight, which took place around 1614. He makes an analogy between air and water saying that just as water compresses us from all sides when we are immersed in the bottom of the sea, the air also compresses us because we are immersed in the depths of its immensity. We do not feel the compression because our body is made of such a property that it can withstand this compression very well without suffering injury. He emphasizes that the weight of the air is actually very great and that this is the real cause of the difficulty in producing a vacuum. If this resistance can be overcome, a vacuum can be produced.

The explanation of Torricelli shows that it is the weight of the air that equilibrates the column of mercury. From his account of the experiment, the height of the column of mercury is related to the size of the atmosphere, which from the observation regarding the twilight is about fifty or fifty-four miles. Torricelli believes it is less than these values otherwise the column of mercury would be larger. The exact scheme through which the column of the liquid is related to the weight of air was developed by Pascal who clarified the concept of atmospheric pressure and introduced the hydrostatic principle, the basis of his theory of hydrostatics [9].

12. Conclusion

We have examined the metaphysical theories of motion and matter developed in the classical period of ancient Greece by Democritus, Plato, and Aristotle, as well as some other theories that were great influenced by Aristotle. These theories intended to explain the real world through metaphysical concepts, which, although claimed to be the real essence of things, are not liable to be observed or measured experimentally, or are not clearly and unambiguously defined.

The main ideas of Aristotle concerning motion are summarized as follows: motion is caused by a mover, or being in motion means being moved by something, projectile motion is explained by peristasis, velocity is proportional to the motive power and inversely proportional to the resistance of the medium, velocity of a falling body is proportional to its weight. Aristotle held that the void is impossible because, among other reasons, the motion of a body in the void would be instantaneous.

Philoponus rejected the peristasis theory of Aristotle and explained the motion of a projectile by an impressed force. A similar explanation was given by Avicenna, and a further development was given by the impetus theory of Buridan. Although these theories grew out of the criticism on Aristotle, they did not change his proposition that motion needs a motive power. A fundamental step in the theory of projection motion was given by Galileo by the use of a precise meaning of velocity in rectilinear motion. This precise meaning of velocity allowed Galileo to define uniformly accelerated motion which he assumed was that followed by bodies in free fall or descending on inclined planes.

On reading texts on metaphysical theories is tempting to interpret some terms according to the present scientific theories. This is not unusual and occurs particularly in text-books, and the theory is said to be an anticipation of a more recent theory. This occurs for instance when it is said that Democritus theory is an anticipation of the Dalton atomic theory of matter or of the kinetic theory of matter. It may be a reflection of our unconscious thinking of past theories as approximation to modern theories or to a final theory that we think exists in nature. If we give a modern interpretation to the metaphysical terms, we are fabricating a theory which is not the original one.

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