Chapter 5
Pneumatics, the Thermoscope and the New Atomistic Conception of Heat

In Galileo's day, once important scientific questions had been formulated, they often found wide circulation by means of letters or notes sent to friends and acquaintances. Today's name for one such scientific problem is "Bardi's problem," for the question had been presented to Galileo by Count Bardi di Vernio (1534–1612).[1] The problem, and even more so its solution, represent a paradigmatic logical model for the period before instruments had been invented to measure temperature. The problem suggests investigating why a person feels cold when he goes into a body of water like a river during the summer, and even colder when he comes out, but, going back into the water, finally feels comfortable. There were several variations of this problem after his first formulation. For example, the condition was often added that, before the person goes bathing, he spends time in the shade where he feels neither cold nor hot and, when he comes out of the water, he returns to this shady location.[2]

Galileo's solution to the more elaborated version of Bardi's problem, on the basis of those empirical data provided by the human senses, is the following:

> The problem is to be solved in the following way. In a room we have a tub full of water, and this has been there, for example, 15 days long: one person comes, takes off his clothes and goes into the tub: it is clear that he feels much colder in that water than he felt before he entered it; from which one can conclude that, if air and water are placed in the same location, that is with the same heat or coldness, the water will be always perceived to be colder than the air. We therefore say that, if the air has 2 degrees of cold, the water has 10 of them: hence another water which has only 6 of them, appears cold in comparison with

[1] Bardi's problem was formulated with the help of Father Grienberger at the *Collegio romano* in 1614 and presented ("recited," as they called it) at the institute's weekly meeting by Bardi himself. Bardi sent Galileo the text with the problem as an attachment to a letter: Giovanni Bardi to Galileo, June 20, 1614, in *EN*, XII:76–77. See also Francesco Stelluti to Galileo, June 28, 1614, in *EN*, XII:78 and Giovanni Bardi to Galileo, July 2, 1614, in *EN*, XII:79–80. For Galileo's relationship with Giovanni Bardi, especially concerning the frameworks of the Jesuits in Rome and their mutual connections to Christoph Grienberger, see Blackwell (1991, 135–137).

[2] There is textual evidence of both formulations of Bardi's problem in Galileo's legacy. The first formulation is reported in a textual fragment, and the second is one of the problems Galileo intended to discuss in his unpublished treatise of *Problemi spezzati*. For the fragment, see *EN*, VIII:610. For the formulation of the problem in the treatise, see *EN*, VIII:599. The treatise of the *Problemi spezzati* was introduced in the previous chapter. For more details, see p. 132.

M. Valleriani, *Galileo Engineer*, Boston Studies in the Philosophy of Science 269,
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> the air that has 2 of them, but much hotter in relation to the water that has 10 of them. Now, given this, the person who goes bathing in the Arno, when he is naked in the shade, enjoys the moderate coolness of the air, which has only two degrees of cold; but when he goes into the water of the Arno, he feels its cold which is of 6 degrees (I say 6 degrees and not 10 because the ardent Sun, which hits it over a distance of many miles, took away 4 of them [degrees of cold] from it [the water]); and therefore, in comparison with the air, which has only 2 of them, the water seems very cold to him. This person then gets out of the Arno and returns to the shade, wet and covered with a very thin veil of water so slight that, as soon as the person is under the tree in the shade, the water will have already obtained the 4 degrees of cold back, taken away from the Sun. Hence from the 6 that it had before, it gains 10, so that the person who bathed no longer feels 6 degrees of cold but 10: and therefore while he stays under the tree he feels extreme cold. But if he then goes back diving and enters the water, which has 6 degrees of cold, losing four degrees of cold, it seems to him as if he had entered a mild bath (*EN*, VIII:599).

Galileo was wrong in considering the temperature of water exposed to the rays of the sun to be lower than that of the air over the water. However, this was the general conviction before the thermoscope, or the thermometer, was applied to such investigations.[3] Once the thermoscope appeared, Galileo, based on the knowledge of pneumatics that he shared with Italian Renaissance hydraulic engineers of his day, also turned to the question as to how such a pneumatic instrument actually worked. This research then led Galileo to an atomistic conception of heat, which, once it was further developed in the form described in his *Il Saggiatore* of 1623, allowed him to address Bardi's problem again, this time coming up with a completely different solution.

Although Galileo never published anything directly concerned with the thermoscope or the investigations using or testing it, he nevertheless expended great effort in working with such an instrument. Most of the evidence of such research is represented by letters and fragments, most of which have never previously been evaluated by historians, so that even Eduard Dijksterhuis felt obliged to state that Galileo analyzed and postulated a heat doctrine in his *Il Saggiatore* as a consequence of a casual event, which he did not describe further (Dijksterhuis 1983, 473–475).

The thermoscope was the first instrument built to measure temperature. In Galileo's day, however, no modern concept of temperature had yet been formulated. The semantic instruments used to speak about temperature were "degrees of cold" and "degrees of heat," which were sharply distinguished definitions. Once the thermoscope was equipped with a scale, it became a thermometer. Galileo is one of several, who, more or less simultaneously at the beginning of the seventeenth century, and in different geographic locations, "invented" the thermoscope: the first instrument that could be used to obtain information about the degrees of heat and

[3]Galileo's solution to Bardi's problem, as given in the treatise of the *Problemi spezzati*, was not written before he invented the thermoscope, for the outline of such a treatise was compiled by his son during the final years of his life. Although the history of this fragment is unknown, its argument is relevant as a paradigmatic example of a method for solving problems related to temperature before the invention of the thermoscope.

cold without appealing to the human senses. The thermoscope circulated for about ten years before being transformed into the thermometer. Thus, the thermoscope represents a small but crucial link in the chain back to the earlier era, when people judged temperature only on the basis of their own senses, and the current era, when we cannot even conceive of life without such an instrument and the information it provides.

But the thermoscope was not really invented: more accurately, it was the result of a conceptual reshaping process which took place at the beginning of the seventeenth century. The thermoscope is a pneumatic device that functions on the basis of the phenomenon according to which the air contained in a vessel dilates when the temperature of the device's surroundings increases, and contracts when the temperature decreases. Considered only as a pneumatic device rather than as an instrument to measure temperature, this instrument is a very old technical realization. It is not even possible to determine when such an instrument appeared for the first time. Certainly, such devices became extremely common during antiquity up to the Hellenistic era, for works on pneumatics, such as those by Philo of Byzantium and Hero of Alexandria, clearly show how this natural phenomenon was used to power plenty of pneumatic devices, many of them conceived as kinds of trick fountains. Theoretical speculations about those principles on the basis of which pneumatic devices work have their origins in antiquity as well. The earliest surviving textual evidence is a poem composed around 460 BC by Empedocles of Agrigentum, entitled *On Nature* (Philo of Byzantium and Prager 1974, 5–6). The appearance of the thermoscope, therefore, is the result of a process of reconfiguration of an old device. The process of reshaping the ancient pneumatic device into an instrument for measuring temperature is also closely related to the reception and transformation of ancient pneumatics that took place in Italy during the Renaissance, which focused mainly on the work of Hero of Alexandria.

Moreover, pneumatic devices that worked on the basis of the same phenomenon as the thermoscope were very common in Galileo's day. Such instruments were used in the medical field, for example, or simply kept as fashionable objects. Bleeding cups, milk pumps for nursing mothers, *calendaria*[4] and many sorts of fountains and water gardens were probably the most common devices among the instruments of the thermoscope type. Considered from this perspective, therefore, it is hardly appropriate to speak of the invention of the thermoscope. The thermoscope is an ancient device, which was conceptually reshaped in order to meet needs and *desiderata* that emerged between the end of the sixteenth and the beginning of the seventeenth centuries, and remain established today.

To fully understand how the appearance of the thermoscope led Galileo to his atomistic conception of heat, and how this could happen essentially because of

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[4] *Calendaria* were pneumatic devices, often hung on the outside of doors, which, thanks to the daily motion of the liquid upward and downward, were considered to be a kind of time-keeping device.

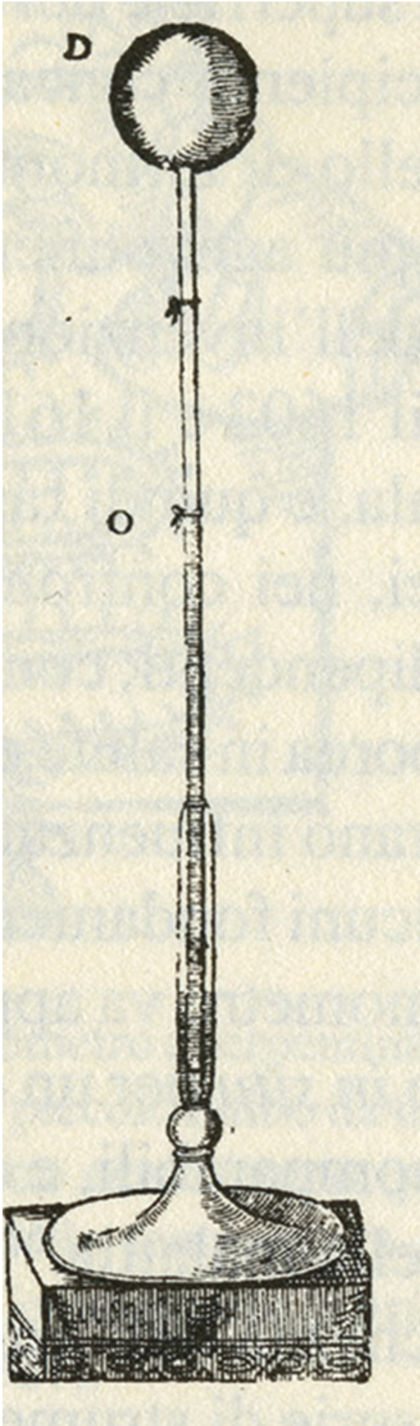
Galileo's sharing pneumatic science with his contemporary hydraulic engineers, first the details of the thermoscope's composition will be shown. Second, the emergence of the instrument will be described briefly, along with the context within which it was first applied. The thermoscope and its first applications for scientific purposes soon challenged some aspects and core principles of the Peripatetic doctrine concerned with natural motion, such as the Aristotelian processes of condensation and rarefaction. The instrument presented a further challenge not only because of the empirical data it provided, but also and especially because the Aristotelian doctrine apparently was not able to provide a satisfactory explanation for the way the instrument worked. This point already had been recognized before the thermoscope appeared, and had led to the formulation of new pneumatic principles as a consequence of the process of reception and transformation of ancient pneumatics, mainly through the work of hydraulic engineers. Ultimately, the new pneumatics of Renaissance engineers was the background from which Galileo's new pneumatic principles emerged through his studies about the functioning of the thermoscope. Once this whole process has been described, it will be shown how Galileo's first atomistic conception of heat was formulated around 1619, while he was attempting to lay the theoretical foundations for pneumatic devices powered by heat sources, like the thermoscope. Finally, this section will consider the development that led Galileo to his second atomistic conception of heat, as published in *Il Saggiatore* in 1623, and present Galileo's updated solution to Bardi's problem.

The Thermoscope

The first thermoscopes (Fig. 5.1) are instruments constituted of a small vase full of water at the bottom, from which a thin pipe vertically emerges, the upper part of which normally ends with a bowl. The bowl and the upper part of the pipe are empty or, more accurately, filled with air. When the air is heated, for example, by exposing the bowl to the rays of the sun, the air expands, pushing the water downwards. When it is cooled it contracts, pulling the water upwards as it tends to create a vacuum. The expansion and contraction of air are consequences of changes not only in temperature, but also in pressure. In fact, the first thermoscopes were actually a sort of thermo-baroscope. Recognition of this characteristic, still unknown at Galileo's time, led to the second generation of instruments, known as the liquid in glass thermometers.[5]

[5] The variability of air pressure became known toward the mid-seventeenth century, and the invention of the liquid in glass thermometer apparently can be attributed to Ferdinando II, Grand Duke of Tuscany. For a detailed historical view of the emergence of the liquid in glass thermometer, see Knowels Middleton (1966, 27–39). For the history of the barometer, and especially, the discovery of the sensitivity of air to atmospheric pressure, see Knowels Middleton (1964, Chapters 3 and 4).

Fig. 5.1 Example of an early thermoscope (Sanctorius 1646, col. 29-30)



The thermoscope as a *perpetuum mobile* If the components of the thermoscope are implemented appropriately, the thermoscope can be built in very large sizes. When a large thermoscope is placed outdoors with the part containing air covered, the instrument simply shows a kind of "perpetual" movement of the water. For this reason instruments like the thermoscope were initially known best as *perpetuum mobile*.[6] The sixteenth and seventeenth centuries are distinguished by the search for a perpetual motion machine, a search encouraged by the aristocracy's promises of generous rewards for successful inventors. Especially in northern Europe, the appearance of these instruments is often related to the attempt to have them recognized as perpetual motion machines. The only difference between a perpetual motion machine and a thermoscope, besides the larger dimensions required for a more marvelous effect, was in fact that the "inventors" of the perpetual motion machines kept silent about the principle on the basis of which their devices worked, generally claiming that the motion of the water corresponded to the flow and ebb of the seas.

The Emergence of the Thermoscope

Many historians have dedicated parts of their works to the emergence of, first, the thermoscope, and then the thermometer. Most, if not all of these studies, focus mainly on questions of priority, although it is quite impossible to show who invented the thermoscope first.[7] In fact, the thermoscope probably started circulating in market squares, from the stalls of which it was transformed into a scientific instrument by people like Galileo, who applied it to their research. In the literature of the previous century, however, there is general agreement about the first four men who are supposed to be "inventors" of the thermoscope: Galileo, Sanctorius Sanctorius (1561–1636), Robert Fludd (1574–1637) and Cornelius Drebbel. Usually forgotten in the history of the thermoscope and of the thermometer is Giovan Francesco Sagredo. In part together with Galileo and in part alone, he is the author of the most important developments of this instrument during its early years.

Galileo's early use of the thermoscope Discussing the appearance of a device of the "flow and ebb" sort with his friend Cesare Marsili (1592–1633) in Bologna in 1626, Galileo himself reports that he has been familiar with this sort of device after having made "a similar amusing device" twenty years earlier when he was in Padova. Thus, Galileo had worked with such instruments as far back as 1606.[8]

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[6] As mentioned, such a device was also called *calendarium*.

[7] See, for example, Favaro (1966, I:193–212), Caverni (1972, I:265–298), and Hellmann (1920).

[8] Galileo to Cesare Marsili, April 25, 1626, in *EN*, XIII:319–320. Galileo told Marsili that it was a device which works on the basis of the principle according to which air expands when heated and contracts when cooled. Since Marsili also reported that the author of the device called it "Flow and Ebb *perpetuum mobile*" and suggested using salt water, Galileo added that this was a trick to conceal the truth. This letter has never been cited as evidence for Galileo's construction and use of the thermoscope.

Fig. 5.2 Replica of Galileo's thermoscope (Istituto e Museo di Storia della Scienza, Firenze. Inv. 2444)

In a letter to Fernando Casarini of 1638, Benedetto Castelli (1577–1644), one of Galileo's most important pupils, wrote:

> [...] I remembered an experiment showed to me already more than thirty-five years ago by our Lord Galileo, which was that, taken a small decanter of glass with the size of a small chicken egg, and a neck about two spans long and as thin as a grain stalk, and once the mentioned small decanter was well heated by means of the palms of the hands, he turned it upside down with its mouth into a vase placed below, where there was a bit of water. By making the small decanter free from the heat of the hands, the water immediately started ascending along the neck and went over the level of the water of the vase for more than one span; that effect then was used by the same Lord Galileo to build an instrument to examine the degrees of heat and cold (Fig. 5.2).[9]

Galileo had demonstrated the pneumatic phenomenon to Castelli earlier than 1603. However, being able to set up such an experiment does not amount to Galileo's conceiving of such a device as a thermoscope. This instrument cannot be considered "invented" until somebody decides to perform the demonstration described

[9]From Benedetto Castelli to Ferdinando Cesarini, September 20, 1638, in *EN*, XVII:377–380.

by Castelli with the purpose of measuring temperature. Castelli himself stated that Galileo made such an instrument “later.”[10]

One can therefore conclude that Galileo applied the fundamental pneumatic phenomenon to build the thermoscope during the period between 1603 and 1606.

Drebbel’s *perpetuum mobile* The Dutch machine maker Cornelius Drebbel,[11] to whom the invention of the thermoscope is also often ascribed, never built a single thermoscope. In his day Drebbel was famous for his astronomic clocks and his *perpetuum mobile* of the flow and ebb variety. Contrary to what is often believed, Galileo came into indirect contact with Drebbel and was aware of his work by 1610 at the latest.[12] Drebbel made his first perpetual motion machine in 1604 for King James I of England, who highly appreciated the device. In 1610 Drebbel moved to Prague, to the Court of Rudolph II, Emperor of the Holy Roman Empire, for whom he assembled the same device which had made him famous in England. Drebbel’s “great machine” was constituted of a semicircle of glass, which contained water or another more visible liquid. A tight-fitting lid then was used to cover the other components, namely those containing air. At the beginning of Drebbel’s stay in Prague, on October 1610, the Tuscan ambassador at the court of the Emperor, Giuliano de Medici, wrote Galileo that “a Flemishman is there and pretends to have found the perpetual motion machine.”[13] Giuliano de Medici described the machine, adding that Kepler would not accept that it was a *perpetuum mobile* until he understood the principle on the basis of which the machine works, which Drebbel took care to keep under wraps.[14]

The name Drebbel came to Galileo’s ears again in 1612, when his former pupil Daniello Antonini (1588–1616) wrote him from Brussels, where he was serving as a military officer. Antonini learned that James I had a *perpetuum mobile*, namely the

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[10] A third indication for Galileo’s invention of the thermoscope is represented by a passage in Viviani’s *Racconto*. Viviani relates that Galileo invented the thermoscope, that is “those instruments of glass, with water and air, in order to distinguish the mutations of heat and cold and the variety of temperatures of [different] places,” during the first years of his stay in Padova, after 1592 (*EN*, XIX:607).

[11] For an exhaustive overview of the life and works of Cornelius Drebbel, see Tiere (1932).

[12] In 1611 Drebbel asked Giuliano de’ Medici to provide two pieces of Galileo’s glass in order to have them polished and made into telescope lenses for the emperor. According to the Tuscan ambassador, His Caesarean Majesty was spending a great deal of time with Drebbel investigating technical contrivances. For more details, see Giuliano de’ Medici to Belisario Vinta, November 14, 1611, in *EN*, XI:234, and Giuliano de’ Medici to Belisario Vinta, November 11, 1611, in *EN*, XI:235.

[13] Giuliano de’ Medici to Galileo, October 18, 1610, in *EN*, X:448–449.

[14] Galileo asked the Tuscan Ambassador for more details about the device later in 1610 (Giuliano de’ Medici to Galileo, November 29, 1610, in *EN*, X:478–479). At the end of the same year Martin Hastal, probably an ex-pupil of Galileo, who was also in Prague and was usually involved in the scientific life of the court, allowed Drebbel and Galileo to meet indirectly and entertain each other with conversation on the *perpetuum mobile*. For more details, see Martin Hastal to Galileo, December 19, 1610, in *EN*, X:491–492. Without great success, Favaro tried to collect more details on Martin Hastal, who certainly met Galileo and was very familiar with Venice and Padova. For more details, see Favaro and Galluzzi (1983, I:600–606).

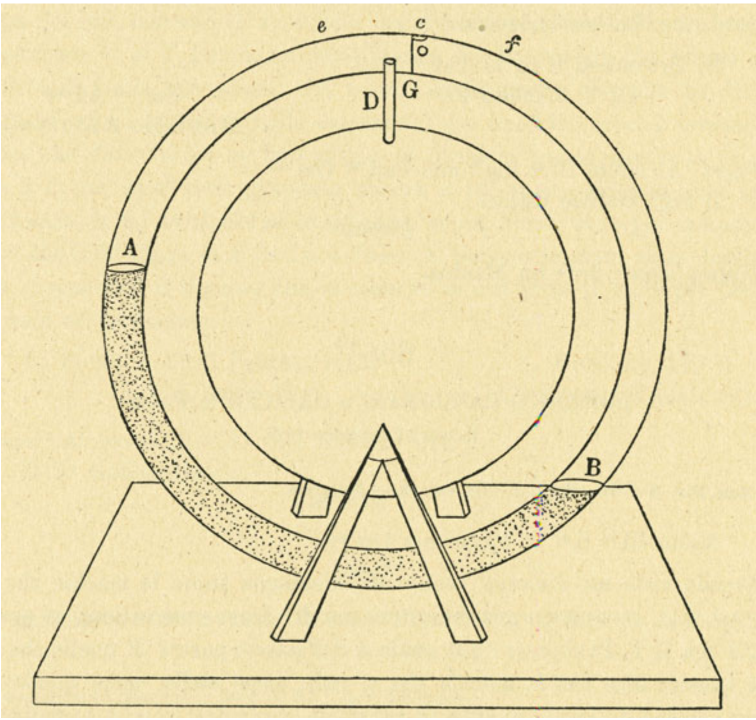

Fig. 5.3 Daniello Antonini's drawing of Cornelius Drebbel's *perpetuum mobile* (*EN*, XI:275)

one from Drebbel (Fig. 5.3). Informed about the shape and dimensions of the device, he immediately understood its function and constructed a similar one. As he wrote Galileo, he had grasped how to make one of those machines "thanks to the experiments with the small decanter," that Galileo performed in Padova when Antonini was his private student.[15] Antonini made a perpetual motion machine which was straight and vertically positioned rather than circular in shape. The prince under whom Antonini was serving immediately wanted to see the machine, and Antonini decided to give it to him as a gift rather than asking for money or privileges. Like Antonini, Drebbel never used his instrument to measure temperature and therefore he did not "invent" the thermoscope.[16]

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[15]Daniello Antonini to Galileo, February 4, 1612, in *EN*, XI:269–270. Unfortunately, it is not possible to know with any precision when Antonini took private lessons from Galileo. Otherwise this would amount to further evidence relevant for dating Galileo's first use of the thermoscope. For the translation of the entire letter, see pp. 227ff.

[16]Knowels Middleton tried to change the meaning of this conclusion, to which he also arrived, adding that Drebbel certainly could have made a thermoscope if he had wanted to do so. Yet this remark does not seem terribly useful. For more details, see Knowels Middleton (1966, 21).

Sanctorius' early use of the thermoscope Five months after Antonini's letter, in 1612, Giovan Francesco Sagredo communicated to Galileo that their mutual friend Agostino da Mula had been at the fair of the patron saint of Padova, where he saw:

> [...] an instrument by Lord Sanctorius with which one measures the cold and the heat with the divider. Finally he communicated to me that it is a large bowl of glass with a long neck [...].[17]

Sanctorius Sanctorius was a doctor, practicing mostly in the Venetian Republic, but also in some other Italian and European countries thanks to his renowned foundation of what the history of medicine calls the Iatromechanical School (or Iatrochemical or Iatrophysical). A member of Galileo's Venetian circle of friends, he was particularly well acquainted with the family Morosini, in whose house the group of scholars often met.

In the first edition of his *Commentaria in artem medicinalem Galeni*, published in 1612, Sanctorius presented the instrument for the first time:

> I wish to tell you about a marvellous way in which I am accustomed to measure, with a certain glass instrument, the cold and the hot temperature[18] of the air of all regions and places, and of all parts of the body; and so exactly, that we can measure with the divider the degrees and ultimate limits of heat and cold at any time of day. It is in our house in Padova and we show it very freely to everybody.[19]

Probably in response to this public invitation, Agostino da Mula went to Sanctorius' house in Padova to see the instrument, as Sagredo told Galileo. Hence, in 1612 Sanctorius had at his disposal an instrument made of glass, constituted of a great bowl with a long neck. The water was placed in the lower part. As the instrument certainly lacked any scale, the levels of liquid along the neck were recorded using a divider and therefore a ruler to measure its opening.

Fludd's thermoscope The Welsh doctor Robert Fludd had practiced mostly in Oxford, apart from six years traveling through continental Europe starting in 1598. In 1609 he became a member of the College of Physicians, where he practiced until his death.[20] Fludd aspired to construct a cosmic theory, in the context of which the effects of light and darkness and of heat and cold were to play a relevant role. He published, in 1617, an account of the pneumatic phenomenon of air expansion caused by heating (Fludd 1617, 30). Sherwood Taylor was able to show that both Fludd's apparatus and its description were taken from Philo of Byzantium's *De ingeniis spiritalibus*, a manuscript he may have possessed (Sherwood Taylor 1942). Fludd did not publish the first illustration of his thermoscope until 1626 (Fludd

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[17] From G. Francesco Sagredo to Galileo, June 30, 1612, in *EN*, XI:350. For the translation of the entire letter, see pp. 229ff.

[18] Sanctorius used the concept of "temperamenta" which does not correspond exactly to the English "temperature." This may mean that not only the degrees of cold and heat, but also the general climatic status of the environment are taken into consideration.

[19] Sanctorius 1612, Part III, Cap. LXXXV, Particula X, col. 62. Translation from Knowels Middleton (1966, 9).

[20] For an extensive work on Robert Fludd's work and life, see Sherwood Taylor (1942).

1626), and he polemized against the many people who considered themselves to be the inventors of the instrument.

Telioux's thermoscope The *Bibliothèque de l'Arsenal* in Paris holds a manuscript written in Rome in 1611, by a certain Telioux (Telioux 1611). In the manuscript a thermometer equipped with a scale is illustrated. The analyses by J. A. Chaldecott (Chaldecott 1952) and Knowels Middleton (Knowels Middleton 1966, 10–13) concur with the conclusion that Telioux did not test the instrument himself, but rather was reporting something he had heard or seen about it. If this conclusion is true, in 1611 the thermoscope presumably was about to become a very common instrument, and thus already known outside the Venetian circle to which Galileo and Sanctorius belonged.

Excluding Drebbel from the ranks of those who apparently first used the device to measure degrees of cold and heat, it seems certain that Sanctorius had a thermoscope in 1612, Fludd published his first description of a thermoscope in 1626 and, at the beginning of the seventeenth century, Galileo was already analyzing those pneumatic phenomena he would later use as the basis for building his thermoscope.[21] Telioux's manuscript, however, provides hints that the thermoscope was probably not "invented" by people like Sanctorius and Galileo. It may be that they merely picked up a technical curiosity that was already in circulation, perhaps conceptually reshaped by vendors on the market square, and applied it for scientific purposes. In any case, by 1624 the thermometer was very well known and probably a standard product sold in many workshops and markets (Leurechon 1624, Problem LXIX).

From the Thermoscope to the Thermometer

In 1638 Fludd published an illustration of a scaled thermometer (Fludd 1638, 2). In the same work, he also gave an explanation on how to determine a scale for the instrument (Fludd 1638, 4). Sanctorius presented his thermometer in 1630 (Sanctorius 1630, Chapter LIII, col. 762). In order to obtain a scale for the instrument, he first determined terms of comparison for its extremities (hottest and coldest) so that he could divide the scale as he wished. He found those terms in the "coldest snow" and in the "hottest fire of a candle."

The development extending from the first thermoscope to a thermometer equipped with a scale can be followed in greater detail, however. In fact, it was during this phase that Galileo and, above all, his friend Giovan Francesco Sagredo, played a significant role and, perhaps for the first time, arrived at the idea of providing the instrument with a scale.[22]

[21] On the basis of the epistolary exchange between Galileo and Giovan Francesco Sagredo, one can conclude that Galileo ascribed to himself the paternity of the invention of the thermoscope and that Sagredo acknowledged it. For more details, see G. Francesco Sagredo to Galileo, May 9, 1613, in *EN*, XI:505–506. For the translation of the entire letter, see pp. 231ff.

[22] Telioux's manuscript, which is dated 1611, shows an illustration of a thermometer. However, the text does not refer to that picture which, therefore, may have been added later.

Sagredo's first thermometer The epistolary discussion between Galileo and Sagredo concerned with the instrument lasted for almost three years, from 1612 until April 1615. In the same letter in which Sagredo informed Galileo about the Sanctorius thermoscope in 1612, he added that:

> [...] I immediately applied myself to producing some of them very exquisitely and beautifully. I make the ordinary ones with an expenditure of four Lira each, that is, a small water vase, a small decanter and a glass siphon. My method of production is such that I can assemble up to ten of them within one hour. The nicest one I made was produced by means of a small flame. It has the size and the shape of the one in the drawing included here,[23] with all its parts. I am waiting to hear that you have made *mirabilia magna*.[24]

Sagredo first became aware of the existence of Sanctorius' thermoscope on the occasion of the celebration of the patron saint of Padova on June 13, and his letter is dated June 30. During a period slightly longer than two weeks, therefore, he was already so expert that he was able to assemble ten thermoscopes in one hour. After this short time, too, he already attempted to build instruments of several shapes, sizes and quality, in reference to both the material and its manufacture. Moverover, Sagredo wanted to obtain a thermoscope from which information about the temperature could be read more easily, that is, he presumably wanted to abandon the method of measurement by means of a divider, as required by the first of Sanctorius's instruments, to achieve another one provided with a scale. One year later Sagredo had a new thermometer able to show temperature differences as great as "100 degrees" between one room of his house and another.[25] Although Sagredo left completely unclear the method he used to provide the instrument with a scale, almost two months later, in July 1613, he triumphantly wrote Galileo that he had succeeded in nearly perfecting the instrument![26]

Sagredo's standardization of the scale In 1615 Sagredo felt confident enough to shift his attention from the method of constructing the instrument to the conception of the thermometer itself. In other words, he performed experiments which would have resulted in an instrument provided with a scale, whose characteristics were somehow communicable. He informed Galileo that:

> [...] two days ago, when it snowed, my instrument displayed 130 degrees more heat in this room than what [it showed] two years ago during a time of very rigorous and extraordinary cold. The same instrument, immersed and buried in the snow, displayed 30 degrees less, that is, only 100.[27]

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[23] This drawing is now lost.

[24] From G. Francesco Sagredo to Galileo, June 30, 1612, in *EN*, XI:350–351. Author's italics. For the translation of the entire letter, see pp. 229ff.

[25] G. Francesco Sagredo to Galileo, May 9, 1613, in *EN*, XI:505–506. For the translation of the entire letter, see pp. 231ff.

[26] G. Francesco Sagredo to Galileo, July 27, 1613, in *EN*, XI:544–545. For the translation of the entire letter, see pp. 233ff.

[27] From G. Francesco Sagredo to Galileo, February 7, 1615, in *EN*, XII:140. For the translation of the entire letter, see pp. 239ff. Sagredo's observation corresponds to what Sanctorius published

Sagredo performed long series of experiments, recording all outputs, in order to provide a scale with communicable terms of comparison:

> But then, immersing [the instrument] in snow mixed with salt, it displayed a further 100 [degrees] less. I believe that it really displayed even less, but one could not see it because of the hindrances [caused] by the snow and the salt. Since, at the hottest point of the summer, it had displayed 360 degrees, one can see that salt added to the snow increases the cold by as much as one third of the difference between the greatest heat of the summer and the greatest cold of the winter.[28]

Sagredo chose two terms of comparison for the hottest and coldest, the two extreme points which, in reference to his own scale, were reached by the liquid over two years of observations. Finally, in order to compensate for their incommunicability, he provided the observational tables of data collected over the same period.[29]

Galileo's and Sagredo's technical tests Once a scale had been achieved, Sagredo was all the more motivated to continue with this field of research. He investigated ways to improve old thermoscopes and thermometers and searched for new and more efficient shapes.[30] He interrogated Galileo about his thermoscope and research with it and discovered that he had attained an even more advanced state of knowledge than his friend had.[31] Both Galileo and Sagredo noted that the ascending motion of the water along the neck was irregular, that is, it did not always show the same characteristics given the same situation. These irregularities were certainly caused in part by the fact that the thermoscope was actually a thermo-baroscope, that is, because it was sensitive to atmospheric pressure. When they believed, therefore, that they were dealing with two identical situations for which they supposed the instrument must show the same degree of cold or heat, in fact they were neglecting the effect of atmospheric pressure, which may have varied significantly.[32]

Irregularities in the ascending motion could have had other causes, however. They were also caused by different viscosities of the water, for example, or of the other liquids often used in the thermoscope.[33] Because of this problem,

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fifteen years later. Sagredo, like everybody else during his time, thought in terms of degrees of cold and of degrees of heat.

[28]From G. Francesco Sagredo to Galileo, February 7, 1615, in *EN*, XII:140. For the translation of the entire letter, see pp. 239ff.

[29]Knowels Middleton pointed out the accuracy of Sagredo's observation: "If we might take the extreme summer and winter temperatures in Venice in those years to be about 34º and −5º, this would bring the mixture of ice and salt to a −18º, a very likely value" (Knowels Middleton 1966, 10).

[30]G. Francesco Sagredo to Galileo, March 15, 1615, in *EN*, XII:156–158. For the translation of the entire letter, see pp. 241ff.

[31]G. Francesco Sagredo to Galileo, April 11, 1615, in *EN*, XII:167–170. For the translation of the entire letter, see pp. 244ff.

[32]In order to create identical situations to which the thermoscope could be applied, one could, for example, apply the flame of a candle.

[33]Wine was often used instead of water in order to improve the visibility of the scale and so to increase the ease of measurement.

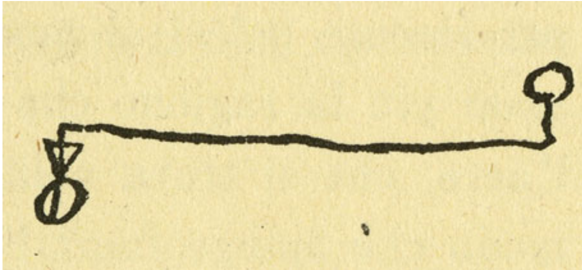

Fig. 5.4 Illustration of Sagredo's bent thermoscope (*EN*, XII:168)

Galileo experimented with thermoscopes equipped with internally broader necks, as Sagredo confirmed he had as well. After these experiments Galileo went back to using thin-necked thermoscopes, while Sagredo, who dedicated more time to the observation of the behavior of the instruments, after comparing observations, concluded that instruments equipped with broader necks worked more accurately.

Sagredo further informed Galileo that he had performed several experiments with different sorts of instruments: one also equipped with a small upper decanter of air and a long neck, where the water ascended and descended along the neck without escaping from it; another one provided with a neck bent twice so that the motion of the liquid was horizontal rather than vertical, probably believing that one cause of the irregularities of the ascending motion of the liquid was that the water was forced to move in a motion that was not natural, the natural one being downwards toward the center of the Earth (Fig. 5.4). After this phase of experimentation Sagredo abandoned these differently shaped instruments, recognizing that the best ones were those equipped with a broad vertical neck.[34]

Finally, Sagredo applied himself to investigating other aspects of the movement exhibited by the liquid in the instruments:

> The best and most perfect instruments I made were with a neck as broad as a finger, referring to the internal part of the neck over which I had blown at the furnace of Murano a vase whose volume corresponds to three or four glasses, using the mentioned instrument in the way Your Lordship writes. In this way I have had three of them made in different sizes, and which have worked now for almost three years in such harmony with each other that it is marvelous. These I have observed for over almost one year, one, two, three, four, five, six, up to eight times a day, with such correspondence that from those observations I have achieved a table of correspondences and equations among them. First I have seen that they work with the absolute same proportion, during both extreme heat and extreme cold, so that each time

[34]A further suggestion by Galileo was to decrease the height of the scale. This was rejected by Sagredo. One of the irregularities demonstrated during ascending motion was that different heights were reached by the liquid in supposedly identical circumstances. Galileo's advice, therefore, certainly provided a method to make the error less evident. Sagredo justified his decision to oppose Galileo by explaining that his suggestion had no theoretical foundation. For more details, see G. Francesco Sagredo to Galileo, April 11, 1615, in *EN*, XII:167–170. For the translation of the entire letter, see pp. 244ff.

> I see one of them I guess, by using the table, the degree of the other two, sometimes with a variation of give or take two or three degrees.[35] [...]. So, changing these instruments a little because of the slightest occurrence, they change more or less depending upon whether they are more or less exposed to those occurrences, either because they are close to the apertures of the room, or to the persons, or to the lights, etc. Moreover, since some of them have thicker and some thinner glass, it is conceivable that not all of them change over the same period, but, should some alterations in the temperature of the surroundings occur, the thinner one is the first to sense and show it. Concerning the instruments with a very thin neck, as those of Your Very Excellent Lordship, you should accept that the viscosity of the water and of the wine also causes variation. Therefore I decided to use instruments of such a size, that, when one takes away the lower vase, the neck empties out.[36]

Since Sagredo and Galileo believed that the irregularities showed by the thermoscope were due to particular characteristics of the instrument itself, Sagredo sought a way to obtain high-quality measurements by constructing a set of instruments of different sizes proportioned to each other so that he could apply all the thermometers simultaneously for each measurement.

Empirical Data Provided by the Thermoscope

The thermoscope and the first thermometer were investigated by Sanctorius, Galileo and Sagredo: three friends, all of whom were involved in the Venetian cultural circle during the first fifteen years of the seventeenth century. During this period the instrument experienced wide diffusion because of its application to scientific purposes. From its inception the thermoscope was also applied both in medicine and in what could be called a preliminary stage of modern meteorology.[37] The first consequence of the application of the thermoscope to scientific problems was the discovery that many empirical data provided by the human senses are incorrect. As will be shown, this represented a first challenge to Aristotelian doctrines.

Early scientific use of the thermometer At Galileo's time meteorology was not yet established. At this early stage, meteorological phenomena were often discussed together with completely different subjects like, for example, those concerned with the temperature of the interior of animals. Moreover, empirical observations had yet to be organized, and not even the necessity of standardizing the instrument had been

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[35] Considering that the hottest day of the summer corresponded to 360°, 2 or 3° of difference were small fractions of 1°C.

[36] From G. Francesco Sagredo to Galileo, April 11, 1615, in *EN*, XII:169. For the translation of the entire letter, see pp. 244ff.

[37] The oldest evidence of the use of the thermometer in the field of meteorology in modern terms is Leurechon (1624). See, in particular, Problem LXIX. Modern meteorology emerged when networks were created that were able to collect data from standardized instruments. The first network in this sense was created by the *Accademia del Cimento* during the second half of the seventeenth century. On the emergence of modern meteorology and the role played by the first scientific networks, see Daston (2008). For a general introduction to the work of the *Accademia del Cimento*, see Knowels Middleton (1971) and Boschiero (2007).

fully recognized. Giovanni Battista Benedetti achieved the recognition of the former complex of problems concerned with temperature, in particular, in his *Diversarum speculationum mathematicarum et physicarum liber*, published in 1585 (Benedetti 1585).

Benedetti's work, which was written before the thermoscope came into common use, is devoted primarily to critiques of the opinions of the Peripatetics. In a chapter entitled *De raro et denso nonnulla, minus diligenter à Peripateticis perpensa* (Benedetti 1585, 191–194), Benedetti discussed a series of phenomena for whose solutions the thermoscope would have provided a great impulse. Summarized, the relevant problems are the following: (1) why animals' breath can be seen in winter; (2) why, if one draws water from below ground during the winter, it emits steam; (3) why subterranean water is hotter than that above the surface during the winter; (4) whether animals' stomachs contain more heat during the winter than during the summer; (5) why, if during the summer cold water is introduced into a vase of glass or silver, it "sweats"; (6) what the cause of the winds is; (7) why fog remains at rest in the place where it originated.

Aristotle's processes of condensation and rarefaction Obviously some of the questions listed by Benedetti are phenomena that would have been investigated in the framework of modern meteorology, but most certainly were not. What these apparently different phenomena had in common at the beginning of the seventeenth century were the principles on the basis of which they were explained by the Aristotelian commentators. These principles were those of condensation and rarefaction, as Aristotle described these processes in his *Meteorology* (Aristotle and Goold 1987, 369A10–369b3).[38]

Condensation and rarefaction are processes on the basis of which natural motions occur. They take place when matter, which exists in a particular form, such as water, for example, changes its form, for instance, into vapor (air). The extension of volume, which is a quality of the form and not of the matter, increases while passing from the form of water to the form of air. In this sense, when a process of rarefaction takes place, this involves only the form and not the matter. It is not appropriate to speak of the rarefaction of matter. The rarefied body then becomes lighter than the body from which it originated, and this is the reason why it eventually moves upwards. The process of condensation works in the opposite direction. Obviously, any process of rarefaction is accompanied by an increase in temperature; and processes of condensation by a decrease. According to Aristotle, condensation and rarefaction always imply a change in form, that is, a change in volume, a change in temperature, a change in weight and therefore a change in natural location. The

[38]In his *Meteorology*, more precisely, in the fourth book, Aristotle approached the issue of element transformation also from the perspective of corpuscolar visions (Newmann 2001, 145–153). Although the fourth book of Aristotles' *Meteorology* became fundamental within the framework of Aristotelian alchemy, this part of the doctrine does not seem to have played any role in Galileo's research.

most convincing application of this doctrine was to furnish an explanation of the water cycle.

Galileo's scientific investigation with the thermoscope Galileo, too, investigated those typical phenomena discussed by the Aristotelian commentators, some of which were listed by Benedetti, on the basis of the Aristotelian principles of condensation and rarefaction. For example, he applied his mind—but not yet his thermoscope—to the widely discussed phenomenon of steam from well water during the winter. Before the thermoscope was applied, it was commonly believed that well water is hotter during the winter than during the summer, both because this corresponded to the sensation of immersing a hand into the water, and because during the winter such water gives off steam. In his critical mind and on the basis of solid observation, Galileo had already noticed:

> That the smoking of the waters of the wells during the winter does not come from the heat, it is manifest: because the linens which dry under the Sun, during the winter give out smoke and during the summer not; one sees breath during the winter and not during the summer, etc. (*EN*, VIII:636)

In February 1615, Sagredo, after having applied the thermoscope, wrote Galileo:

> With these instruments I clearly see that the water in our wells is much colder during the winter than in the summer. For my part, I believe that the same thing happens in live fountains and subterranean locations, although our senses consider these in a different way.[39]

According to the Aristotelian doctrine, ice was the result of the process of condensation applied to water. Thus ice was supposed to be colder and heavier than water.[40] However, since ice does not sink into the waters, for example, of a river, as it was supposed to, the measurement of the temperature of the ice, the water and the surrounding air when this phenomenon happened was considered to be one of the most urgent open questions when the thermoscope finally appeared.

An undated text fragment by Galileo shows how Galileo himself applied his mind to this extremely topical issue:

> The very cold air of the north wind is colder than the ice and the snow: to confirm this, one can bring close to the instrument, during those weathers, some snow or ice, and the wine will evidently descend. Moreover, to confirm this further, a vase full of water and introduced into water will not freeze over, but it will do so if placed in the air. Moreover the waters of the rivers should freeze at the bottom where they are more distant from the air, and not at the surface, where they are very close to the air, but the contrary happens, hence etc. (*EN*, VIII:635)

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[39] From G. Francesco Sagredo to Galileo, February 7, 1615, in *EN*, XII:139. For the translation of the entire letter, see pp. 239ff.

[40] The Aristotelian doctrine was evidently contradicted by the observation that, when ice forms in the rivers, this happens not at the bottom of the river but on its surface, and it does not then sink, as it would have to if it were heavier. However, this contradiction proved not to be an obstacle to considering Aristotle's doctrine as correct, for it was a functioning explanatory theoretical structure for many other natural phenomena.

Sagredo, too, devoted some of his research with the thermoscope to this issue. In May 1613 he informed Galileo that:

> With these [instruments] I speculated about several marvelous things, like, for example, that the air in winter is colder than the ice and snow, that the water now [May 9, 1613] seems to be colder than the air, that a small amount of water is colder than a large amount, and other such similar perceptions. Our Peripatetics cannot give any resolution for these, to such an extent that some of them (among whom is also our Gageo[41]) are so far off track that they do not yet understand the cause of the first operation, since they believe that one should see an opposite effect, because, since heat (as they say) has an attracting virtue, it should be that, when the vase is warmed, it pulls the water toward itself.[42]

The data provided by the thermoscope were not in agreement with those expected from the application of the Aristotelian theories.[43] But this was not yet enough to declare such theories and principles, like those underlining the processes of condensation and rarefaction, to be wrong. The appearance of the thermoscope challenged the Aristotelian doctrines in a much deeper way, however. In particular, when the thermoscope appeared, an important process of reception and transformation of ancient pneumatics had already taken place. It is the combination between the output of the process of transformation of the general theoretical principles of ancient pneumatics, mainly undertaken by engineers during the second half of the sixteenth century, and speculations about the functioning of the thermoscope itself, which not only presented a profound challenge to some aspects of the Aristotelian doctrine, but also led Galileo to his atomistic conception of heat. It is at this point that Galileo took advantage of the knowledge of pneumatics he had learned from engineers, especially during his youth.

The Reception of Ancient Pneumatics

The thermoscope is a pneumatic device powered by a heat source. When the heat source is applied, the air dilates or, in Aristotelian terms, it rarefies. Thus, not only was the thermoscope applied to study those natural phenomena which were traditionally explained on the basis of the processes of condensation and rarefaction, but its own functioning was explained on the basis of these same processes.

According to Aristotle, the process of the maturation of fruits could be described in terms of condensation and rarefaction. When the thermoscope appeared, Galileo tried to formulate a theory on the process of maturation of fruits by comparing it

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[41] Gageo is a sarcastic Venetian distortion of the name Gaio. Sagredo is referring to the Aristotelian philosopher Bernardino Gaio, whom he knew personally.

[42] From G. Francesco Sagredo to Galileo, May 9, 1613, in *EN*, XI:506. For the translation of the entire letter, see pp. 231ff.

[43] The discovery that air can be colder than ice was still reason for great research efforts by the members of the *Accademia del Cimento* toward the mid-seventeenth century, who ideated many experiments to analyze the phenomenon of freezing.

with the functioning of the thermoscope itself. Galileo's idea is preserved in the form of a fragment:

> In the same way, that is, from the operations of heat and of cold, all of the fruits and crops mature. Because, if we consider the structure and the construction of these, we first see that the grape is constituted of berries, or we want to say blisters, and this is seen apparently in the grape where each berry is a blister; it is similar in pomegranates, figs, watermelons and others: since these blisters are full of humors, when the heat of the Sun comes, it presses them out and empties them, pushing out some of that humor so that they are withered in the evening; but when night falls and the air cools down, those blisters fill themselves with new humor, and more than they had sent out the day before, and therefore those blisters become much more capacious; and by means of this alteration they mature *making the same effect that the instrument makes*:[44] which is confirmed by the fact that, in the morning, they are very hard (*EN*, VIII:635–636).

Fruits mature just as the thermoscope works, with the only difference that berries can become more capacious whereas the glass of the thermoscope cannot. The heat of the day rarefies the air in the blisters of the grapes, pushing out their humor. When air condenses (contracts), the plant can produce its humor again. The only condition is that the plants have to produce a little bit more humor each day, which is then correspondingly pushed out by the increasing temperature from spring through late summer.

Although Galileo's fragment is undated, it is nevertheless possible to recognize that his idea of the way the thermoscope works expressed in the period between 1612 and 1615 showed an important distinction from that expressed in this fragment. Between 1612 and 1615 Galileo actually accepted the assumption about the functioning of the thermoscope that had been formulated by hydraulic engineers encountering ancient Hellenistic works on pneumatics for the first time during the Renaissance.

The reception of Hero's *Pneumatics* In Galileo's day in Italy, the reception of Hellenistic pneumatics was for the most part limited to the pneumatics of Hero of Alexandria. Hero's *Pneumatics* was probably originally written during the first century AD. This work contains a collection of technical applications and a theoretical introduction to pneumatic principles, revealed in the *proemium*.[45] Considering the longest version of Hero's *Pneumatics*, as Schmidt reconstructed it philologically (Hero and Schmidt 1899), there are only four technical applications that work on

[44] Author's italics.

[45] Schmidt's German translation of Hero's *Pneumatics* is considered here as a reference work: Hero of Alexandria and Schmidt (1899). In the following: Hero and Schmidt (1899). As Schmidt was able to show, there were numerous Greek manuscripts of Hero's work circulating in Italy during the early modern period. Not all of the circulating manuscripts contained the integral work, but most of them did include the theoretical introduction by Hero. Schmidt was also convinced that not all of the seventy-nine devices he listed were originally Heronian. He also considered the valve to be a hydraulic machine. Although the tremendous relevance of the Heronian valve for technological development cannot be denied, it is not, however, an application of a pneumatic principle. For more details, see Hero and Schmidt (1899, *Supplementum*, pp. 3–53).

the basis of the same principle as the thermoscope, that is, the principle according to which the volume of air changes when the temperature changes.

The versions of Hero's work circulating in the geographic areas Galileo frequented during his lifetime did not correspond with Schmidt's reconstruction. As regards the transmission of Hero's *Pneumatics* in Latin, one translation was relevant for Galileo: the translation by Federico Commandino, published posthumously in 1575 (Hero and Commandino 1575). Although this was not the final version Commandino intended to publish, because he died before it was completed, it is nevertheless held to be the *editio princeps* which eventually served as a great impulse for the process of diffusing Hero's *Pneumatics*. Its sixteenth-century propagation in Italian was indeed based largely on Commandino's translation. In 1582 Bernardo Davanzati (1529–1606) translated only the *proemium*,[46] while the first Italian translation of the entire work was accomplished by Oreste Vannocci Biringucci, also in 1582 (Hero and Vannocci Biringucci 1582).[47] In 1589 the Italian translation by the hydraulic engineer Giovan Battista Aleotti appeared. He was employed by the Duke of Ferrara (Hero and Aleotti 1589).[48] Aleotti's translation, which is very rich in technical applications, some of which were very new and introduced explicitly for the first time, is particularly relevant because of the commentaries he wrote on Hero's theoretical explanations. Finally, Alessandrino Giorgi translated Commandino's work into Italian with the explicit intent of making the *editio princeps* more understandable, since Commandino's published translation was not the final version and therefore still contained many convoluted passages. Giorgi's Italian translation was published in 1592 (Hero and Giorgi 1592).[49]

Pneumatic technology Concerning pneumatic applications, most of Hero's descriptions are of ludic devices that reflect the extremely advanced status of pneumatics during the entire Hellenistic era. Most of the devices he described were decanters, designed to accomplish a wide variety of tasks: Hero's *Pneumatics* includes a description of a sort of automatic wine dispenser, for example, and of awe-inspiring devices like doors that open without being pushed. The technology Hero employed, however, was the same technology applied to machines like the water lifting machines that supplied whole cities.[50] In Galileo's day, far more than

[46]Davanzati's translation of Hero's *proemium* was transcribed and published much later, in 1862. The manuscript seems to be lost (Hero et al. 1862).

[47]Published in http://www.echo.mpiwg-berlin.mpg.de/content/pratolino/sources/ Accessed October 2009. Transcription by M. Valleriani and T. Werner. For a detailed analysis of Vannocci Biringuccis's theoretical commentary work on Hero's *Pneumatics*, see Valleriani (2007). Oreste Vannocci Biringucci was a nephew of the famous engineer Vannoccio Biringuccio, author of *De la pirotechnia*, published in 1540.

[48]For an extensive study on Giovanni Battista Aleotti, see Fiocca (1998).

[49]Giorgi resolved to have the typographer of Commandino's work print his work as well, and even used the same engravings for the illustrations.

[50]For an introduction to Hero's *Pneumatics* and Hellenistic technology and science, see Russo (2001). Hero also left a work concerned with the construction of the automata. The technology employed for the functioning of these ludic devices, a technology able to exploit hydraulic

the ludic aspects of pneumatics could be experienced in everyday life. One instrument, which had been in use for many centuries and still was during his day, was the cupping glass for bleeding. This instrument was constituted of a vase divided horizontally into two parts. Once the lower part was warmed up, the glass was applied to the skin on the side of the upper part. Cooling the glass down slowly, the contraction of the air in the lower part was transmitted to the upper one by means of an air valve, which could be opened at will. Thanks to this contraction, then, the blood was sucked out, apparently with quite beneficial effects. The cupping glass for bleeding and the thermoscope thus work on the basis of the same principle. Another popular device in Galileo's day, whose functioning followed the same principle, was a milk pump for nursing mothers.[51]

Though the interest in pneumatics, which experienced a very high degree of articulation during the Hellenistic era, never disappeared during the Middle Ages, it certainly grew enormously from the thirteenth century on, and especially during the early modern period (Valleriani 2007), as apparent in the intensification of translations and commentary works at this time. In the publications, however, the ludic aspects seem to prevail. In fact, it was very easy to apply pneumatic principles to conceive water games, and the best locations to place such games were clearly gardens. In 1615, the famous architect and engineer Salomon de Caus (1576–1630), who oversaw the construction of the Palatina Garden in Heidelberg, published his *Les raisons des forces mouvantes* (Caus 1615), in which he described several machines and new pneumatic devices, among them some powered by heat, including a fountain that works using the rays of the sun (Fig. 5.5).

Pneumatic theoretical principles The reception of Hero's *Pneumatics*, moreover, also brought to general attention Hero's theoretical framework, on the basis of which the functioning of these devices is explained, and which is expressed in Hero's *proemium*. According to Hero, air is material and constituted of particles; among the particles are interstitial vacua, which can become larger or smaller due to the action of external factors (Hero and Schmidt 1899, 4–5). Hero focused his explanation in particular on air's capacity to contract. He gave the example of a sphere into which one blows forcefully and then closes its opening with a finger. If one then immerses the sphere into water and removes the finger from the opening, it is possible to detect a certain amount of air exiting the sphere violently. According to Hero, if there were no interstitial vacua in the body of air, it would not have been possible to blow more air into the sphere. The violence of the exiting air is due to the tendency of air to return to its natural state, that is, to the natural dimensions of the vacua. The interstitial vacua cannot only contract, but also enlarge. If, for example, the air is sucked out from the same sphere, according to Hero it is easy to detect that

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energy, was the same one used for mills. In particular, see Russo (2001, 152–159). For a general introduction to ancient technology, see also Schürmann (1991).

[51] The instrument for nursing mothers is cited and described by Giovanni Battista Aleotti. For more details, see Hero and Aleotti (1589, 8), Valleriani (2007), and on pp. 177ff in this chapter.

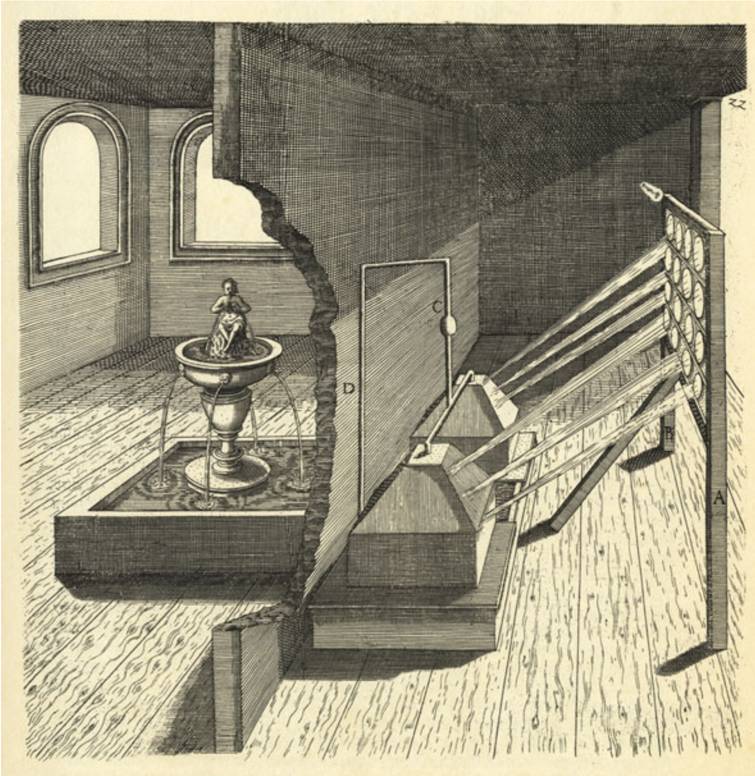

Fig. 5.5 Solar-powered fountain (Caus 1615, Table 22)

a greater vacuum was “pulling” against the exit, because the vacua tend to return to their natural dimensions (Hero and Schmidt 1899, 8–11).

When a source of heat is added, the Heronian system becomes a little more complicated. When air is heated, it becomes a sort of corrupted body, because of the action of the element Fire, so that the air particles become thinner and eventually exit their container through the pores of the material. For this reason, the interstitial vacua are supposed to become larger because they “compensate” for the reduction in volume caused by the loss of particles. When the heating process stops, the enlarged interstitial vacua tend back to their natural state and thus “pull” the surrounding matter (Hero and Schmidt 1899, 10–11).

Although Hero postulated the existence of vacua between the particles that constitute a body, his general framework remained Aristotelian. For Hero the natural state of a body was also connected directly with its natural place. The world in which these phenomena take place is still the Aristotelian sublunar world, where bodies are constituted of the four Elements and their changes are related to a change in their natural position. Heating air or sucking it out from a sphere are violent actions that interrupt the natural motions of these bodies. Finally, Hero completely refuted the idea that an external vacuum, one which is not related to particles constituting a body, can exist.

When the Heronian interstitial vacua change their dimensions, a change in temperature,[52] a change in the extension of the volume, and a motion take place, as in the case of the Aristotelian principles. The only difference is that Hero did not introduce the distinction between form and matter, which means that when all the changes take place, there is still no change in form. This is what actually happens in pneumatic devices. According to Aristotle, the contraction of air is an aspect of the more general process of condensation, which brings a body to change its form. While this solution was still absolutely convincing with reference to meteorological phenomena such as rain, Renaissance engineers soon discovered that it was not sufficient to describe and explain how air can contract but still be air, that is, not enter into any general physical process of transformation, such as Aristotelian condensation.

Transformation of Hero's theoretical principles Since Hero's conception very clearly challenged the Aristotelian one, concerned with similar phenomena explained on the basis of the principles of condensation and rarefaction, most of those who translated and commented on Hero's work during the Renaissance could not avoid facing his theoretical framework. Once large-scale diffusion of Hero's text had been achieved, a theoretical debate arose because the intellectual equipment of engineers and professionals like Oreste Vannocci Biringucci, Giovanni Battista Aleotti, Galileo and Giovan Francesco Sagredo consisted primarily of Aristotelian doctrine, which appeared able to furnish an explanation of the same phenomena. Hero's principles contradict Aristotelian doctrine not only with regard to the principles of condensation and rarefaction, but also, and especially, because they suppose the existence of interstitial vacua. Engineers like Oreste Vannocci Biringucci and Giovanni Battista Aleotti, in particular, deliberately contributed to the theoretical debate that arose during the propagation of Hero's ideas.[53]

Aleotti's conception of heat The last word on this matter, among the Italian engineers of the sixteenth century, fell to Giovanni Battista Aleotti. His new interpretation of the functioning of pneumatic devices powered by a heat source, in particular, led him to abandon both the Aristotelian and the Heronian theoretical approaches. Aleotti explained his theory by means of an example, that is, with a direct description of the pneumatic milk pump for nursing mothers:

> These [the women] take a glass cruet with a neck on the upper part, which is wide enough to be able to contain the nipple of the breast, and they warm up its body [of the cruet] very well by means of fire until the heat, penetrating the thinness of the glass through the pores, pushes the air out from it and fills the body of the cruet with a very thin vapor, and when

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[52] According to Hero's principles, however, a change in temperature takes place only when the pneumatic device works by applying a heat source.

[53] For a detailed description of the theoretical positions assumed by engineers during the process of receiving Hero's *Pneumatics*, and of the way such a process ended up, first, in a transformed science of pneumatics, and also with the abandonment of Aristotelian principles, see Valleriani (2007, 2009b).

> the mentioned body [the cruet] is warm enough, they immediately place the opening of the neck of the cruet at the breast, placing the nipple into it, and since that thin igneous vapor cannot remain in that [the cruet], it exits through the vacua of the glass, through which it [the vapor] penetrated it [the glass], and so begins rising upwards to its place, although from the air around, it is transmuted into aerial substance, and since through these *meatus*,[54] which are very thin, the air cannot enter, and since the vacuum cannot exist, that body, which cannot stay empty, immediately pulls milk from that breast, and by emptying it [the breast], it [the cruet] fills itself, and when it is completely full, it ceases pulling [...].[55]

While Hero's heat corrupts and makes particles of air thinner, so that they escape from the vase, in the case of Aleotti heat is a thin vapor which penetrates the vase and pushes away the air simply because heat is a body, which needs space and occupies a volume. This is what could be called a mechanical conception, because heat is seen as an object with a certain extension and ability to move other bodies. Since, after all, heat is a body, when it escapes the glass, milk is pulled in order to avoid the generation of vacuum. Aleotti therefore formulated a new conception of heat in order to determine the pneumatic principle, on the basis of which pneumatic devices powered by a heat source work.

Galileo as a Pneumatic Engineer

Galileo was well aware of how pneumatics developed among engineers during the Renaissance. First of all, he had the opportunity to share in such a development thanks to what has been called his apprenticeship in pneumatics. The first chapter showed how close Galileo's connections were to the workshop of the engineer Bernardo Buontalenti. In 1569 Buontalenti was commissioned by the Grand Duke Francesco I to construct the entire garden of Pratolino.[56]

The garden of Pratolino According to Sgrilli (d. 1755), an engineer in charge of maintaining the garden of Pratolino who wrote a complete description of it in 1742 (Sgrilli 1742), at every corner, in every artificial cave, by every statue there was a water game, where visitors could be suprised by jets of water. Water games

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[54]Plural of the term "meatus," used in archaic English with the meaning of "small openings," "holes," "pores."

[55]"Queste pigliano una ampolla di vetro con il collo tanto nella parte superiore largo, che sia cappace del capitello della mammella, et riscaldano con il fuoco di essa il corpo ben bene fin che il caldo penetrando per li vacui la sottigliezza del vetro ne scaccia l'Aria riempiendo il corpo dell'ampolla di sottilissimo vapore, et quando è ben bene riscaldato detto corpo subito si pongono la bocca del collo dell'ampolla alla mamella dentro imponendovi il capitello, et perche quel sottil vapore igneo non puo star ivi renchiuso se n'escie fuori per quei vacui del vetro per gli quali entrò, et per levarsi in alto al suo luogo s'invia Se ben dal circomposto aria è trasmutato in sostanza aerea, et perche per questi meati, che sottilissimo sono non vi puo entrar l'aria non potendo esser vacuo subito quel corpo che, non può star voto tira da essa mammella il latte, et votando la viene à riempir se stesso, et ripieno a fatto, non piu tira [...]" (Hero and Aleotti 1589, 8). Author's italics.

[56]There is a massive body of literature concerning the garden of Pratolino. Due to their full coverage of the subject and historical sources, the texts that deserve mention above all others are Ulivieri and Merendoni (2009), Zangheri (1987), Dezzi Bardeschi (1985). For specific studies concerning pneumatics and the garden of Pratolino, see Valleriani (2007, 2009b, 2010, Forthcoming a).

Fig. 5.6 Fountain-parkway in the garden of Pratolino (Engraving of Stefano della Bella in Sgrilli 1742)

were implemented in every architectural element, including stairs, where water was sprayed out against pedestrians from each step (Sgrilli 1742, 12). The garden was then enriched with innumerable fountains and baths, and even a hot water supply (Sgrilli 1742, 14). One boulevard, 292 meters long, was lined with fountains that could project water not only vertically, but also from one side of the boulevard to the other so that the water formed a parabola, a few meters long, under which people could walk comfortably (Fig. 5.6) (Sgrilli 1742, 22). Hydraulic organs (Valleriani 2010) were installed both inside the villa of the garden and outside (Sgrilli 1742, 7 and 20). Gigantic systems of automata, also powered by means of hydraulic energy, rounded out the Heronian program.

Buontalenti's interest in pneumatics was not limited to mere practical realizations. Both Davanzati's and Vannocci Biringucci's translations of 1582 were actually completed at the request of the famous Tuscan engineer, who was about to start working on the garden of Pratolino after having completed its villa in late 1580 (Valleriani 2007). It also seems, finally, that Buontalenti built a perpetual motion machine which was able to lift up great quantities of water without the aid of any mechanical device. Although there are not enough details to conclude that such a device was of the flow and ebb variety like Drebbel's, this seems quite probable (Fara 1988, 204–207).

Galileo as a designer of pneumatic devices While Tuscan engineers were building first the garden of Pratolino, and then the one of Boboli, the young Galileo approached the science of pneumatics in the workshop as it was received by hydraulic engineers. This is then the material background, which, as special problems like the meteorological ones emerged, served as the framework for Galileo's work on and with the thermoscope. However, his attention to the science of pneumatics was not limited to his youth and the period when he constructed the thermoscope. Galileo remained a renowned and recognized expert on pneumatic devices throughout his entire life.

First, Galileo certainly possessed two of the mentioned translations of Hero's *Pneumatics*. He had Commandino's translation, as is clear from the comparison between Commandino's book and a letter Galileo wrote in Padova in 1594 that was sent to Alvise Mocenigo in Venice, in which he described an oil lamp.[57] The other translation Galileo possessed was the one by Giorgi of 1592, as emerges from the partial inventory of Galileo's library published by Favaro (Favaro 1866, 54).

As early as 1611 Galileo served as a consultant on pneumatics to Antonio de Medici, who ordered him to describe the design and the functioning of a fountain to Francesco Maria del Monte in Rome.[58] The hot phase of Galileo as a pneumatic designer started some time later, however. In late July 1613, Galileo sent Sagredo some flasks of his red wine as a gift, which, according to Sagredo, was so good that he could not keep himself away from it. Thanks to Galileo's wine, Sagredo became a pneumatic designer first:

> After the arrival of the very precious wine of Your Lordship, and with this heat, my intellectual purpose lies in measuring that heat while I have cold drinks. [...]. I also found: a decanter that, when the wine passes through it, cools down immediately, and if needed, warms up; some glasses in order to drink it with ice, and another where, once the wine is introduced into it, one can see how many degrees of cold it has taken, and it can also be used to drink; an inkwell that preserves the ink in this hot weather so that it does not dry up, become thick, or make the pen too wet, which is cheap and lasts a long time. After drinking two glasses of the wine of Your Lordship, these inventions came to me so now I hope that, as soon as I have drunk only one of your flasks, I will have invented divine things.[59]

Unfortunately, we shall never know what divine things Sagredo invented that night. The reception of pneumatics started bearing fruit at the beginning of the seventeenth century, not only thanks to engineers commissioned with the construction of marvelous gardens, but also to everyone else who approached this science and its technology with an open mind. In this context, the conceptual reshaping of the ancient pneumatic device in terms of an instrument to measure temperature allowed devices to be developed that were capable of showing and even controlling the temperature of liquids.

Galileo learned from his friend Sagredo that many applications of the same principle could be realized besides the thermoscope; he never forgot this lesson. In

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[57] Galileo to Alvise Mocenigo, January 11, 1594, in *EN*, X:64–65. For the translation of the entire letter, see pp. 219ff.

[58] For more details, see F. Maria del Monte to Antonio de' Medici, April 8, 1611, in *EN*, XI:83–84.

[59] From G. Francesco Sagredo to Galileo, July 27, 1613, in *EN*, XI:545. For the translation of the entire letter, see p. 233.

1627 he was still overseeing the construction of devices like the ones suggested by Sagredo. On June 27, 1627, the military officer Baglioni Malatesta (1491–1540) wrote Galileo from Pesaro that:

> Since I have known that the Very Excellent Lord Don Carlo Barberini has a glass, invented by the high mind of Your Lordship, which shows the degrees of heat and cold that one drinks, I came to the wish of having a drawing of it.[60]

It is impossible to know whether Galileo appropriated Sagredo's invention and told Barberini it was his own. However, Baglioni's letter makes evident that at the time Galileo was also known as a designer of pneumatic instruments. Galileo's response to Baglioni shows that he offered to have the glass built in Florence and dispatched to him.[61] Presumably, Galileo already had at his disposal a network of such experienced craftsmen in building pneumatic devices that it cost him less time and effort to have the glass made and send it than to prepare a written description. Taking advantage of Galileo's generosity, Baglioni asked for two glasses instead of one; at the end of the year, both arrived safe and sound in Pesaro.[62]

The thermoscope, his activity as a pneumatic consultant and the production of drinking glasses showing the temperature of the liquid within are evidence that substantiates Galileo's experience as a designer of pneumatic devices.[63] Galileo presumably was able to accomplish these tasks on the basis of the reception of Hero's work, which he experienced indirectly in the workshop of Buontalenti, who was busy building the garden of Pratolino during this period. In conclusion, these are all of the material conditions which allowed Galileo to investigate the theoretical background of not only the thermoscope, but also of that new pneumatic science which resulted from the process of reception and transformation of Hellenistic pneumatics.

The Functioning of the Thermoscope

When Daniello Antonini, Galileo's former pupil, wrote in 1612 to report that he had built a perpetual motion machine like that of Drebbel in Brussels, he also concluded that, as he learned from Galileo, the thermoscope is a mechanical instrument:

> [...] because I know well that there is no difference between this motion [of the *perpetuum mobile*] and that of a water mill apart from the cause of motion, which is seen by everybody [in the water mill], whereas in this case it is not.[64]

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[60] From Malatesta Baglioni to Galileo, June 16, 1627, in *EN*, XIII:363.

[61] Malatesta Baglioni to Galileo, July 17, 1627, in *EN*, XIII:367–368.

[62] Malatesta Baglioni to Galileo, December 12, 1627, in *EN*, XIII:380.

[63] Galileo was still active as a pneumatic engineer in 1635, when he sent to his friend Micanzio in Venice a design for a fire hydrant. For more details, see Fulgenzio Micanzio to Galileo, Septemer 15, 1635, in *EN*, XVI:310–311.

[64] From Daniello Antonini to Galileo, February 4, 1612, in *EN*, XI:270. For the translation of the entire letter, see pp. 227ff.

Galileo's 1615 explanation of the thermoscope Galileo's precise opinion about the way the thermoscope works, as Antonini learned from him, probably corresponded to the conception he formulated in 1615. This is the first evidence that testifies directly to Galileo's opinion about the way the thermoscope worked, and was formulated by Galileo upon Sagredo's request. Galileo's response was lost, but not so Sagredo's comments on it:

> I understood your opinion about the way those instruments function [. . .] and I would even dare to say [it is] also true, *if it were not for the reason that in itself it is not evident to the senses*. [. . .]. But it satisfies the mind much more than the arguments of the Peripatetics: If, because of the external heat, the air that is inside the warmed glass bowl evidently dilates so that it pushes out the water, it is easy to believe that the heat penetrates the glass. Once it has penetrated there in greater or smaller quantity, it requires more or less space. Since it [the space] cannot simultaneously contain the air and the soft and igneous spirit, the air is obliged to exit the space. In addition, when the external environment cools down, it is believable that the igneous spirit, which is overabundant in the bowl, exits until it equilibrates with the environment. Thus, since the space that contained it becomes empty, the air is obliged to follow, and water or wine after it.[65]

Galileo started by considering the temperature of the air outside the bowl of the thermoscope. When this becomes hotter, the heat penetrates the glass, and, since the latter was already full of air, more space should be produced: The air is pushed down and therefore the water descends. Galileo supposed therefore that heat, in the form of igneous spirit, is a body with a certain and definite extension, so that it would be able to cause mechanically the motion of other and different bodies.

Galileo's opinion is extraordinarily similar to Aleotti's, from which it presumably was adopted. From the end of the sixteenth century on, pneumatic devices were explained either on the basis of the Aristotelian principles of rarefaction and condensation, or on the basis of those principles formulated by the engineers—in particular, those formulated by Aleotti. Galileo, therefore, clearly influenced by the knowledge of the engineers, decided to abandon the Aristotelian approach, at least temporarily, in favor of the mechanical explanation. Because of Sagredo's critique, Galileo later abandoned the mechanical explanation as well and tried to formulate a new pneumatic theory, into which he also integrated a new version of the Aristotelian processes of condensation and rarefaction.

Sagredo's critique and Galileo's experiments Sagredo did not consider Galileo's conception to be evident to the senses, and his explanation was indeed highly abstract, apparently impossible to show in the literal meaning of the word. Galileo took such criticism very seriously and started performing new pneumatic experiments, never before evaluated by historians. The first thing he did after read-

[65] From G. Francesco Sagredo to Galileo, April 11, 1615, in *EN*, XII:167–168. Author's italics. For the translation of the entire letter, see pp. 244ff. In the same letter, Sagredo described an experiment he performed to demonstrate the existance of the void.

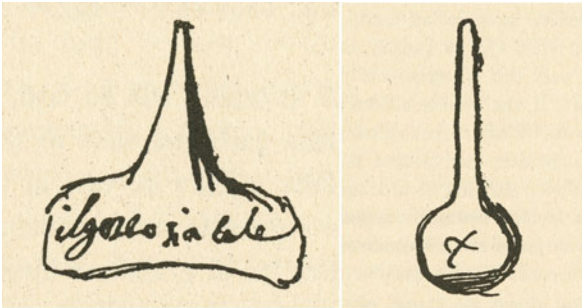

Fig. 5.7 Galileo's notes on for pneumatic experiments to make the igneous spirit visible (*EN*, XII:170)

ing the stirring letter he received from Sagredo was to annotate, on the same folio, a couple of experiments clearly intended to make his opinion evident to the senses:

> 1) Hold an empty decanter over the fire and from the mouth (which has to be very narrow) observe by means of an air valve[66] whether the igneous spirit exits continuously (Fig. 5.7 left).
> 2) Introduce into decanter x a very small quantity of wine, ink, quicksilver, etc. Then, place it over the fire, observe whether the mentioned [things] are consumed, etc. or what it makes (Fig. 5.7 right).[67]

These two experiments were intended to make the igneous spirit evident to the senses and presumably to investigate its characteristics. Obviously Galileo was not able to observe the igneous spirit exiting the flask, although under certain circumstances the air valve might have exhibited some movement. In the second experiment Galileo probably applied an air valve as well. There is no historical evidence on the results of these experiments, but the subsequent progression of Galileo's research on this topic seems to show that they turned out to be inconclusive.

Galileo's second explanation of the thermoscope If the igneous spirit could not be shown to the senses, if its existence could not be verified, it was difficult to affirm that the igneous spirit is a body with a certain extension, which occupies space, and which is able to move other bodies. Probably because of this dramatic problem, Galileo changed his approach completely and formulated a new pneumatic theory. This new formulation is preserved in a textual fragment written perhaps in 1619 or

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[66]The use of an air valve, specific to such an experiment, testifies further to Galileo's familiarity with pneumatic technology.

[67]Notes in Galileo's hand in the margin of the letter from G. Francesco Sagredo to Galileo, April 11, 1615, in *EN*, XII:170. Author's enumeration. For the translation of the entire letter, see pp. 244ff.

shortly thereafter.[68] Galileo's formulation of his new pneumatic theory about the way devices powered by a heat source work is the following:

> At the schools of the philosophers, it is approved as a true principle, that a characteristic of cold is the tightening, and of heat the rarefying. Now, this accepted, be given that the air contained by the instrument has the same temperature[69] as the rest of the air in the room where it is placed; and since these two bodies have the same specific gravity, one does not push away the other [...]. But if the air which surrounds the bowl cools down, because of the displacement of some cooler bodies, the heat particles [*calidi*] contained in the air within the bowl, since they are in a medium [which is] heavier than they are, will ascend, and that air will become cooler than before; and so, because of the principle just mentioned, it will tighten and occupy a smaller space: hence (*ne detuur vacuum*) the wine will ascend to occupy the space left free by the air; and then, having warmed up that air, since it rarefies and needs more space, it will push down the wine, which, since it is heavy, gladly will surrender that place to it; hence it follows that cold is nothing but a loss of heat (*EN*, VIII:634–635).

Galileo first redefined the Aristotelian principles of rarefaction and condensation. Since rarefaction means less weight, and condensation more density and more weight, introducing a cold body into the arrangement intially makes the air in the room colder, that is, heavier. The process of communicating the temperature between the air in the bowl and the air of the room is not specified, but movements are explained in terms of specific gravity. The colder surrounding air is a heavier medium which, therefore, pushes away and upward not that air which is in the bowl, but those components of it which make it lighter (and hotter), in order to obtain equality in terms of specific gravity.[70] These components, finally, are *calidi*, a concept that is intended to specify a form of igneous particles.[71]

Having abandoned the mechanical explanatory model, Galileo saw no alternative but to hark back to the Aristotelian principles of condensation and rarefaction. In order to operationalize them, he had to find a way to explain, first, how changes of temperature can take place without assuming that heat occupies space and, second, how changes in temperature can take place before the Aristotelian principles take effect. Concerning the issue of space, the igneous particles do not seem to have any shape, and no more space is automatically created in the bowl when they leave the air. Concerning the processes of condensation and rarefaction, had Galileo postulated that changes of temperature are their consequence, he would have had

[68] The fragment shows how Galileo approached the idea that heat has a discrete nature. Since he published his conception of heat according to this approach in *Il Saggiatore* in 1623, and since the debate that ended with this publication began in 1619, it can be circumstantially inferred that this fragment was written between 1615 and 1623, perhaps around 1619.

[69] Galileo used the word *temperie*, which denotes not only "temperature," but rather the general situation of the weather or climate.

[70] Galileo's explanatory model, in this case, corresponds to the one used in his *De motu antiquiora* where he approached the phenomenon of free fall in terms of hydrostatic phenomena. For more details, see Van Dyck (2005, 868).

[71] For an introduction to the philosophical background of early modern atomism, see Lüthy (2003).

to address the problem the engineers were facing already, that is, that such processes involve changes in form, despite the fact that no change in form can be observed in the thermoscope, for instance, from air into water. In fact, introducing the *calidi* allowed Galileo to explain how changes of temperature can take place without appealing to the processes of condensation and rarefaction. These start operating only after the *calidi* have left the air and the latter has become colder. At this point the condensation process explains how air contracts and, since no vacuum can exist, the liquid ascends. From this perspective, Galileo's first formulation of the first atomistic conception of heat is a consequence of his integrating some aspects of Aristotelian doctrine into his new theory.

Yet the conclusion of Galileo's fragment that cold is nothing but a loss of heat does not seem to follow from this line of reasoning. This conclusion can be better understood through a mental experiment Galileo relates in his *Discorso intorno alle cose che stanno in su l'acqua* of 1612:

> [. . .] and one sees, thanks to the experiments, this air ascending faster through the water than the igneous exhalations through the air: hence one necessarily concludes that the same emanations ascend much faster through the water than through the air, and that, consequently, they are moved because they are pushed away by the environmental medium, and not because of an intrinsic principle, which is in them, [when the movement is] fleeing from the center, toward which the other heavy bodies tend. [...] in the elementary bodies there is only one intrinsic principle of movement, which is that toward the center of the Earth, and that the only reason for the upwards movement (speaking only about that [movement] which appears as a natural motion) is the pushing away by the medium [which is] fluid and heavier than the mobile; [...] (*EN*, IV:86).[72]

According to the Archiemedean framework, of which Galileo evidently made use (Bertoloni Meli 2006, 6), the only intrinsic motion of the bodies is the addressed motion downwards. Since such a downward motion took place in Galileo's model of the thermoscope when the temperature rose, the cooling process turns out to be only a loss of heat, because the ascending motion resulting from the cooling process is not an intrinsic motion, but rather, of course, one caused by the different specific gravities of the mobile and of the medium. Through the combination of the last fragment and this passage from *Floating Bodies*, it emerges that Galileo was on the verge of superseding the early distinction between degrees of cold and degrees of heat. But Galileo never actually took this step.

The explanation of the way the thermoscope worked is therefore based on the following five principles: (1) the principle of rarefaction and condensation, altered such that they do not involve change of form; (2) nature's abhorrence of a void; (3) the natural inclination of bodies to move toward the center of the Earth; (4) the difference between the specific gravities of the media as the cause of those natural

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[72]For the emergence of this model in Galileo's early text *De motu antiquiora*, see Bertoloni Meli (2006, 52–53).

movements which are not directed toward the center of the Earth;[73] (5) the discrete constitution of heat. The first three principles belonged to the Peripatetic school and were derived directly from Aristotelian doctrine. The fourth principle, namely the introduction of the concept of specific gravity, applied the Archimedean explanatory model for natural motion. The last of the principles, according to which igneous particles exist, seems to be a genuine result of Galileo's analysis of the pneumatic instrument invented to measure cold and heat.[74] Neither in 1612, when he wrote the *Floating Bodies*, nor in 1615 when he exposed to Sagredo his early opinion on the thermoscope, had Galileo yet embraced this view.

Thus, what can be defined as Galileo's first atomistic conception of heat, presumably formulated around 1619, was developed from his work on pneumatics and, in particular, from his attempt to explain the way those pneumatic devices which are powered by a heat source worked. Galileo further developed his conception and published it in *Il Saggiatore* in 1623.[75] Having achieved this final step, Galileo then went back to his roots and attempted to solve Bardi's problem in a new way.

Galileo's Doctrine of Heat

The dispute that led Galileo to the publication of *Il Saggiatore* took place between 1619 and 1623 and concerned the nature of comets, after three of these celestial bolides appeared in 1618.[76]

The dispute behind *Il Saggiatore* A *disputatio* concerning the appearance of the comets was held at the *Collegio romano* in 1619 and originally published anonymously in the same year under the title *De tribus cometis anni MDCXVIII* (*EN*, VI:21–35). The author was the Jesuit Orazio Grassi (1583–1654), against whose

[73]The idea that upward motion is caused by heavier medium might have been mutuated from Galileo's early collaboration with Jacopo Mazzoni during his stay in Pisa as a lecturer of mathematics between 1589 and 1592. In a later work (Mazzoni 1597), Mazzoni clearly described this principle. For more details, see also Bertoloni Meli (2006, 61).

[74]Galileo also attempted to apply his discrete theory of heat to some subjects related to the science of life. Another fragment reports Galileo's opinion about human numbing: "That human beings die numb with cold happens because the environmental cold consumes all those igneous atoms that it finds in the limbs and, therefore, since the natural calor is no more there, one dies" (*EN*, VIII:635).

[75]During the same period other scholars like Giuseppe Biancani and Francis Bacon, for example, tried to investigate the principles on the basis of which the thermoscope works. In his *Sphaera mundi*, Biancani stated that the functioning of the instrument can be explained by means of the principles of rarefaction and condensation, and through the fact that nature abhors a vacuum. For more details, see Biancani (1620, 111).

[76]As a consequence of this dispute, the equilibrium dominating relations between Galileo and the *Accademia dei Lincei* on one side and the Company of Jesus on the other broke down once and for all. This equilibrium had allowed Galileo and the Jesuit natural philosophers to work in a climate of friendly collaboration. The new cultural environment that emerged after this quarrel can be viewed as the source of the political activism which eventually led to Galileo's abjuration. For more details, see Redondi (2004).

text Mario Guiducci, a pupil of Galileo, published a rhetorically quite provocative response—*Discorso delle comete*—in the same year (*EN*, VI:37–108). In his text Guiducci fiercely criticized not only Grassi's opinions, but also those of Tycho Brahe, which were widely accepted among the Jesuits, and of Aristotle. Guiducci's criticisms are elaborated explicitly on the basis of what he claimed he learned from Galileo.[77] The order of the Jesuits, and especially Father Grassi himself, reacted negatively to Guiducci's affront. Father Grassi immediately prepared a severe reprimand entitled *Libra astronomica ac philosophica* and also published in 1619, under the pseudonym Lothario Sarsio Sigensano (*EN*, VI:111–180). Believing Galileo to be the spiritual father of Guiducci's work, Grassi implicated Galileo directly in the quarrel. While Guiducci attested to his paternity of the text in a public letter sent to the Jesuit Tarquinio Galluzzi (1574–1649), Galileo read and annotated Grassi's *Libra astronomica*. In 1622 he sent the elaborated response to the *Accademia dei Lincei* in Rome, whose members decided to publish it a short time later. In late 1623 Galileo's response was published under the title *Il Saggiatore* (*EN*, VI:197–372). *Il Saggiatore* is the last public word by Galileo on this quarrel.[78]

The conception of heat between 1619 and 1621 The point of departure for Grassi's 1619 discussion of heat is the scholastic assumption that heat is caused by motion (*EN*, VI:32). Through Guiducci Galileo criticized this view, objecting that not motion, but friction is the cause of heat. Reproposing Aristotle's famous experiment with the arrow that warms up while flying through the air, Galileo stated that it was erroneus and offered an example that illustrates how heat is caused by the friction between solid bodies. When heat is generated, moreover, at least one of the two bodies is consumed. If there is no consumption, neither can there be any heat (*EN*, VI:55–56). Grassi's reply in the *Libra astronomica* is less a critique than an attempt to reconcile Aristotle with Galileo. He accepted Guiducci's statement, but added that, since there is no friction without motion, then motion is, albeit secondarily, the cause for the generation of heat. Moreover, Grassi's explanation about the generation of heat added two further aspects. First, that the processes of rarefaction and condensation operate such that the consumption of the bodies can be explained as an effect of the combined actions of these principles, on the one hand, and of mechanical friction, on the other. Second, he also took into consideration the friction between bodies which are not solid, like air, for example, in order to redeem the case of an arrow that warms up in flight (*EN*, VI:160–161).

[77] The *Collegio romano* protested that the true author of the text was Galileo himself. Although Guiducci and Galileo always denied that the latter was involved in the compilation of the work, today it has been confirmed that they were lying. In fact, a manuscript by Galileo is preserved in Florence, which makes clearly evident that he prepared the first draft of Guiducci's *Discorso delle comete* (*EN*, VI:672–680).

[78] When *Il Saggiatore* was published, Grassi's superiors prohibited his scholars from publishing any further texts on the same subject, probably after having decided that Galileo's response had surpassed the boundaries of tolerance, and that any action against his work must be of a political nature. Grassi, however, did write another work, published in Paris in 1626 (*EN*, VI:375–500). Galileo also began annotating Grassi's works of 1626 but he ultimately chose to leave his notes in the drawer. Galileo's notes were published by Favaro together with Grassi's work of 1626.

Galileo's admission of failure In 1623 Galileo challenged all of these aspects of Grassi's reply, though in different ways. First he rhetorically rejected the use of secondary causes, stating that, if Aristotle said motion was the cause of the generation of heat, he was not secondarily right, but merely wrong. Second, he approached the principles of rarefaction and condensation with more delicacy. As has been shown above, Galileo applied a modified form of these principles in order to explain the way the thermoscope worked, combining them with the conception of *calidi*. Probably because of the resulting uncertainty about extending these principles' applicability, Galileo admitted to Grassi in *Il Saggiatore*:

> [...] how this business of rarefaction and condensation works, about which it seems to me that Sarsi speaks with great confidence, I would have gladly seen explained in a clearer way, since, to myself, it is one of the most recondite and difficult questions of nature. (*EN*, VI:331).

Faced with these principles Galileo balked. As he admitted, he could not accept the way the philosophical schools used them and when he applied them himself, he combined them with other non-traditional assumptions. The fact that Galileo never published a word about the way the thermoscope worked or about his newly formulated pneumatic principle, and his admission that he was not able to understand the way the processes of condensation and rarefaction work, clearly testify to Galileo's dissatisfaction with his own theory about the functioning of pneumatic devices powered by a heat source.

Galileo's 1623 conception of heat The third aspect of Grassi's conception, according to which friction could occur even among bodies that are not solid, finally gave Galileo the opportunity to disclose the core idea of his new doctrine of heat. Galileo first rejected the rough idea that a stone which, thrown vigorously into the air, can warm up (*EN*, VI:330–331). Then, Galileo rejected the Aristotelian description of heat:

> [...] a true accident, affection and quality which really resides in the matter, from which we feel warm ourselves. (*EN*, VI:347)

The scientific investigation of the temperature of bodies would, according to the Aristotelian doctrine, be based on the relationship between an inherent quality of the matter and a sense, inherent to the perceiving body. Galileo objected against this view, offering a conception of heat as a factor independent of the singular perceiving bodies and, taking advantage of what he had achieved previously, stating that:

> [...] the operation of fire taken alone is nothing but, since it moves, penetrating all the bodies thanks to its greatest thinness, and dissolving them faster or slower according to the multitude and velocity of the igneous particles and to the density or rarity of the matter of those bodies; and of those bodies there are many, which, while dissolving, change into other smaller igneous particles, and it continues the dissolution until it finds dissolvable matters. But that besides the figure, the multitude, the motion, the penetration and the touch, there is in the fire another quality, and that this is the heat, I do not absolutely believe; [...] (*EN*, VI:350–351).

One of the principles Galileo used to explain the way the thermoscope works, namely the discrete nature of heat, became the core idea of his conception of heat:

The action of fire depends solely on the igneous particles of which it consists and on their motions. Fire, which was considered the hottest "body," does not contain heat. The sensation of heat is then easily explained by means of contacts between the perceiving body and the igneous particles:

> [...] those matters which produce and make us feel heat in ourselves, which we call with the general name of fire, are a multitude of smallest bodies, shaped in this way and that, moved with much and much velocity; which, meeting our body, penetrate it thanks to their greatest thinness, and their touch, made during the passage into our substance and felt by ourselves, is the affection which we call heat, glad or troublesome according to the multitude and the smaller or greater velocity of those smallest [particles] which sting and penetrate us, glad is that penetration, thanks to which our necessary and imperceptible transpiration is facilitated, troublesome that, when too great a division and dissolution of our substance takes place: [. . .] (*EN*, VI:350).

The new heat particles are no longer *calidi*, which is a concept suggesting that they are somehow ontologically defined on the basis of the quality "heat" (*caldo*). Instead, the new heat particles are defined only in terms of shape and motion. It is the effect of their encountering and penetrating the body that is called heat. The last Aristotelian residues were thus abandoned, paving the way for Galileo's general atomistic conception of matter, as expressed in the First Day of the *Discorsi* (*EN*, VIII:65–138).[79]

The final solution to Bardi's problem On the basis of the newly achieved conception of matter and heat, Galileo was finally able to furnish a new answer to the old problem of Bardi. A final fragment, undated but attributed here to after 1622, relates Bardi's problem and its solution in an updated form:

> The water placed in a room has the same temperature of the room where it is, since both equally partake of the igneous atoms. The reason why a hand, which is kept in the air and seems hot to you, then cools down when it is put into the water, is the following: if one considers both the external and internal heat [of the hand], while it remains in the air, its own igneous atoms can exit and these cause the heat; but put into the water, its [of the water] particles fill and close the entrances through which the mentioned atoms exit, because the parts of the water are bigger than the porosities through which they escape; and this does not happen in the air, since they find a free field, because they are not kept by the parts of water, since they are smaller than the pores through which they escape: because heat is nothing other than the contact and the tickling of those igneous atoms, which, when they escape, touch the limbs of the body (*EN*, VIII:635).

Galileo's final solution to Bardi's problem is based completely on his general atomistic conception of heat. All of the kinds of matter involved in the problem—heat, air, water—are conceived as constituted of particles. The mechanical interaction among these is the final key to explain pneumatic phenomena and, in general, all of those phenomena concerned with heat.

[79]In particular, for the analysis of the First Day of Galileo's *Discorsi* and, especially, for an interpretation according to which Galileo's atomistic conception of matter should be intended as mathematical rather than physical, see Biener (2004).

The Generation of a Heat Doctrine

During his apprenticeship in Florence, Galileo partook of practical knowledge in the field of pneumatics. The available sources do not allow the precise determination of the extent of Galileo's involvement, for instance, with colossal projects such as the hydraulic and pneumatic engineering for the garden of Pratolino. Certainly, however, his knowledge of the field allowed him to approach pneumatic phenomena as subjects for his teaching activity in Padova. Moreover, Galileo shared theoretical knowledge concerned with pneumatics and developed by hydraulic engineers at the end of the sixteenth century. At this time, in fact, and for certain specific fields of activity, engineers, too, began developing reflective knowledge, basing their investigations on their own experience. Such a process of generation of knowledge followed the same model as, say, the one of the Aristotelian commentators of the *Mechanical Questions*, seen in the previous chapter. Indeed, the hydraulic engineers formulated their theoretical knowledge within the framework of a new, enlarged and commented edition of another relevant work from antiquity, namely Hero's *Pneumatics* (Valleriani 2007). In particular, Galileo shared the then widely circulating view formulated by Giovanni Battista Aleotti and published in his 1589 edition.

Pneumatic devices challenged the Aristotelian doctrine and specifically Aristotle's processes of condensation and rarefaction, and this is the reason why engineers like Aleotti developed a new theoretical approach. From the perspective of Galileo, however, the appearance and especially the advent of a new instrument for use in science, namely a pneumatic device to measure degrees of cold and heat, represented a new challenge to the very theories developed by engineers at the end of the sixteenth century. Confronted with this challenge, Galileo decided to prove his first view by accumulating relevant experience and then to try to create a new theoretical explanation of how the thermoscope worked by resorting to the Aristotelian doctrine and eventually transforming it appropriately.

However, this intellectual undertaking by Galileo was a failure that created the background for developments that went much further: a new conception of heat completely structured on the basis of a corpuscolar and mechanical vision. Once more, therefore, the generation of new knowledge was the result of a process of integrating practical knowledge, directly shared and indirectly assumed via theoretical formulations of sixteenth-century engineers, with the fundamental Aristotelian scientific categories of his time. Galileo's atomistic conception of heat, as published in his *Il Saggiatore* of 1623, is therefore the result of the work of an Aristotelian engineer.