Ancient Pneumatics Transformed during the Early Modern Period

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Abstract

The paper aims to show how sixteenth century hydraulic and pneumatic engineers appropriated ancient science and technology – codified in the text of Hero of Alexandria's Pneumatics – to enter into scientific discourse, for instance, with natural philosophers. They drew on the logical structure, content and narrative style passed down from antiquity to generate and codify their own theoretical approach and to document their new technological achievements. They did so by using the form of commented and enlarged editions, just as Aristotelian natural philosophers had been doing for centuries. The argument aims to detail the exact role of ancient science and the process of transformation it underwent during the early modern period. In particular, it aims to show how pneumatic engineers first tested the ancient technology codified by Hero while carrying out their own practical activities. Once these tests were successfully concluded, in the spirit of early modern humanism they finally presented these activities as being associated with the work of their discipline's most authoritative author, Hero of Alexandria, whose technology was tested during the construction of the hydraulic and pneumatic system of the garden of Pratolino.

Keywords

Pneumatics – Pratolino – Transformation of Knowledge Historians of science and technology consider the early modern period as the epoch during which an intensive process of theoretical and technical renovation and innovation toplace.Driven by favorable economic conditions, this process started along the coasts of the Mediterranean regions due to the intensive exchanges that characterized this area. Most economic capitals invested in new technology from the very beginning, in devices such as windmills that were needed to improve efficiency in agriculture. Soon a technological leadership was established in the southern regions of Christianity that was especially concerned with activities such as shipbuilding, hydraulics, and metallurgy. This leadership then moved on in the direction of northern Europe.[1]

Parallel to the increasing recognition of the economic relevance of technology, the social importance of its authors – engineers, architects, and mechanicians – also increased. This process was literally boosted by a successive fundamental historical change, namely, what is usually defined in history as the revolution of the art of war. The diffusion of heavy but mobile artillery powered by gunpowder radically changed the geographic and cultural landscape. The sixteenth century represents a period of unprecedented investment in military technology. Metallurgy and closely related methods to more efficiently exploit waterpower enabled the production of small metal objects of higher resistance and hardness. Among the objects produced were cannon balls. These new smaller balls, which had impressive penetration power, finally led to a reduction in size and weight of the artillery.

At the time of the First Italian War in 1494, the effects of such technological innovations became visible to everyone. No city or fortress was able to defend itself from the cannons of the French, who invaded the peninsula. That particular moment signaled the ignition of a spectacular process of technological innovation in all related fields: metallurgy, chemistry, architecture, and masonry are only a few of the fields of activity deeply influenced by this revolution. Once heavy artillery achieved a certain degree of standardization during the first thirty years of the sixteenth century, especially due to the work of Maximilian I, a new military and geometric architecture also emerged in response to the new attack strategies developed on the basis of the new weapons. This could be perceived as the principal means of bringing the constant application of mathematical methods to practical activities, which then became a permanent conjunction between mathematics and practical knowledge.

As is typical for knowledge dynamics, the new geometric method of fortification called for new knowledge in all related fields.[2] Mathematical instruments

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[1] For an introduction to early modern economic history, see Larry Epstein, *Freedom and Growth, Markets and States in Europe,* 1300–1750 (London: Routledge, 2000). See also, Richard A. Goldthwaite, The Economy of Renaissance Florence (Baltimore: The Johns Hopkins University Press, 2011).

[2] For an analysis of knowledge dynamics, see the introduction of Jürgen Renn (ed.), *The Globalization in History,* Max Planck Research Library for the History and Development of Knowledge (Berlin: Edition Open Access, 2012).

began to appear in the bags of artillerymen and a new mathematical ballistics emerged.[3]

While technology and military technology pervaded everyday life during the sixteenth century, they also caused an urgent need for mathematics. A myriad of new sciences emerged as a result of re-shaping, re-formulating and developing new aspects of natural philosophy, but they developed under the perspective of mathematics and against a background of real technological enterprises.[4]

Within this framework, however, another fundamental process supported such radical changes, namely the process of rediscovering ancient science. The same idea was established by humanists and developed by carrying, translating, commenting, editing, and later publishing all the works that testify to ancient culture tout court. In this general frame, scientific works were also addressed, though they played a major cultural role later on in the early modern period.[5]

The humanists' work contributed not only to the emergence of the idea of an ancient epoch, but also to the idea of the emergence of a new epoch. The humanists saw themselves and their time as the starting point for this new epoch, which would find its full identity during the early modern period. Consequently, the process of rediscovery of ancient culture and, specifically, of ancient science, cannot simply be seen as a process of reception. On the one hand, the ancient works had to be understood in their historical context and, on the other, they had to be recontextualized in the modern cultural framework.

[3] For the scientific consequences of early modern technological innovations and especially in reference to the revolution of the art of war, see Matteo Valleriani, *Metallurgy, Ballistics and Epistemic Instruments. The Nova scientia of Nicolò Tartaglia. A New Edition* (Berlin: Edition Open Access, 2013), Id., Galileo Engineer, Boston Studies in the Philosophy of Science (Dor-drecht: Springer, 2010).

[4] For an example concerning the emergence of a new science of acoustics from an older philosophical framework and by means of the conjunction of geometry and practical knowl-edge during the seventeenth century, see Matteo Valleriani, "Galileo's Abandoned Project on Acoustic Instruments at the Medici Court," *History of Science*, 2012, 50:1, pp. 1–31.

[5] For the emergence of the idea of the ancient epoch between the late Middle Ages and the early modern period, see Peter Burke, *The Renaissance Sense of the Past* (London: Edward Arnold, 1969). For the role of the humanists, see Leonardo Olschki, *Galilei und seine Zeit* (Halle: Max Niemayer Verlag, 1927; reprint, Vaduz: Klaus Reprint Ltd., 1965), Paul Lawrence Rose, *The Italian Renaissance of Mathematics* (Genéve: Libraire Droz, 1975).

Such recontextualization necessitated a long and elaborate process, which took place at a number of different levels and, especially, within the more general and very dynamic process of cultural change already mentioned. Ancient science was not just received, but rather transformed to establish the very idea of ancient science and furthermore to contribute to the formation of the early modern scientific culture and practice.[6]

In order to understand the meaning of knowledge transformation when referring to ancient science, the present work analyzes the case of transformation of ancient pneumatics during the sixteenth century and specifically from the moment when Hero of Alexandria's work on pneumatics became widely available thanks to the 1575 printed *editio princeps*.[7]

First, the theoretical background of ancient pneumatics in its original ancient context will be analyzed. Focusing in particular on Hero's of Alexandria's *Pneumatics*,[8] the history of the early modern editions of this work will be described. At this stage, the argument will take into consideration the attention dedicated especially to the technological suggestions of Hero and then to his theoretical approach. Concerning pneumatic technology, the work will reconstruct the case of the construction of the Renaissance Tuscan garden of Pratolino, as the early modern transformation process of ancient pneumatics is closely related to this historical event. Finally, the major steps of the appropriation and transformation process and its consequences will be recollected in order to understand exactly how the transformation of ancient pneumatics took place.

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[6] A similar approach, but concerned with the emergence of the theory of resistance of materials in the early modern period, has been developed in Matteo Valleriani, "The Transformation of Aristotle's 'Mechanical Questions:' A Bridge Between the Italian Renaissance Architects and Galileo's First New Science," *Annals of Science*, 2009, 66:2, pp. 183–208. See also Peter Damerow and Jürgen Renn, "The Transformation of Ancient Mechanics into a Mechanistic Worldview," in *Transformationen antiker Wissenschaften*, edited by Georg Töpfer and Hartmut Böhme (Berlin: DeGruyter, 2010), pp. 239–263.

[7] The present work concludes a project that began in 2005. Some of the aspects of the present argument have already been outlined in a series of publications, which will be mentioned along the text.

[8] The edition of Hero's *Pneumatics* referred to in this work is Hero of Alexandria, "Heronis Alexandrini pneumaticorum libri duo," in *Heron Alexandinus Opera*, edited by Wilhelm Schmidt (Leipzig: Teubner, 1899), pp. 1–333. For an English edition, see Marie Boas Hall (ed.), *The "Pneumatics" of Hero of Alexandria: A Facsimile of the 1851 Woodcroft Edition* (London: 1971).

1 Ancient Pneumatics and Hero of Alexandria's Work

Considering the general frame of the ancient theory of elements, pneumatics is a science used to analyze all phenomena that involve movements of at least one of the four elements: fire, air, water, and earth. Ancient pneumatics is usually associated with the functioning of trick vessels, which control and predetermine the movement of one element by means of the technical control of the movement of a certain volume of another. From a theoretical perspective, ancient pneumatics implies the study of nature and behavior of the elements, which, in turn, means the investigation of nature and the constitution of matter.

Pneumatics developed originally as a practical activity and specialization to build devices integrated into water systems such as irrigation and water supply systems. Moreover, small devices such as the water clepsydra have been in use since time immemorial. The first textual references to pneumatic devices can be found in Homer's works. A relevant impulse in developing a science of pneumatics, that is, a codification of descriptions of pneumatic devices and an abstract reflection about the behavior of the elements involved in their functioning took place during the Hellenistic period. According to the studies on ancient pneumatics and hydraulics, it was Ctesibius who in the 3rd century BCE first compiled a treatise completely dedicated to this subject. Although his treatise was lost, the treatise of Philo of Byzantium, written a generation after Ctesibius and apparently deeply influenced by the former one, was handed down to us.[9] The last relevant treatise on pneumatics written in antiquity was compiled in the early 1st century CE by Hero of Alexandria.[10]

Hero of Alexandria's treatise on pneumatics is the work that had the greatest influence on the early modern debate.

The first chapter of Hero's work is dedicated to the explanation of his theoretical principles. The first principle states that air is to be considered a solid body.[11] Though this was debated, the principle did not become a core point of scientific discussions. The second principle, according to which air can con-

[9] Details about the development of a theoretical apparatus of pneumatics are given below in this work. For an introduction to the history of ancient pneumatics, see Philo of Byzantium and Frank David Prager, *Pneumatica* (Wiesbaden: Dr. Ludwig Reichert Verlag, 1974), Astrid Schürmann, "Antike Pneumatik," in *Antike Naturwissenschaft und ihre Rezeption*, edited by Klaus Döring and Georg Wöhrle (Bamberg: Collibri Verlag, 1992), pp. 86–114.

[10] For the dating of Hero's works, see Paul Keyser, "Suetonius "'Nero'" 41.2 and the "Date of Heron Mechanicus of Alexandria*," Classical Philology*, 1988, 83:3, pp. 218–220.

[11] Hero of Alexandria, "Heronis Alexandrini pneumaticorum libri duo" (cit. note 8), p. 4.

tract and expand, caused serious disputes as Hero's explanation was in direct opposition to the Aristotelian doctrine.

According to Hero, air is matter and constituted of particles; among the particles are interstitial vacua, which can evidently become greater or smaller due to the action of external factors. Hero focused his explanation in particular on the air's capacity to contract.

Imagine an open glass bottle: blow into it and then immediately plug the opening. If the bottle is then immersed in water and the plug taken out, one can observe air coming out of the bottle. The explanation of this apparently simple phenomenon created significant problems in ancient times, as it did again toward the end of the sixteenth century.

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 vessel. 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 are not only able to contract, but also to enlarge. If, for example, the air is sucked out from the same vessel, according to Hero it is easy to recognize that a greater vacuum has been created, which "pulls," because the vacua tend to return to their natural dimensions.[12]

If one adds a source of heat, which in modern terms causes the air to dilate, the Heronian system becomes a little more complicated. Hero had to take this into consideration because the pneumatic devices functioning on the basis of these characteristics of air worked mostly using sources such as fire or sunrays. If the 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 the container through the pores of the material. For this reason, the interstitial vacua are supposed to become larger because they compensate the volume that is reduced due to the loss of particles. When the heating process stops, the enlarged vacua tend back to their natural state and thus "pull" the matter around and toward themselves.[13]

Some of the ideas discussed by Hero of Alexandria were not entirely his own. They had been circulating in the context of ancient science for centuries. For instance, they had already been stated by Philo of Byzantium,[14] who, in

[12] Ibid. (cit. note 8), p. 8.
[13] Ibid. (cit. note 8), p. 10.
[14] Philo's *Pneumatics* is a work originally compiled as the fifth book of his *Mechanical Syntax*. Apart from some Greek fragments, Philo's *Pneumatics* survived in both Arabic and Latin as an extensive text. For the Arabic text and its French translation, see Philo of Byzantium and B. Carra de Vaux, *Le livre des appareils pneumatiques et des machines hydrauliques par Philon de Byzance* (Paris: Imprimerie nationale, 1902). For the entire tradition of the Latin texts and further medieval and early modern manuscripts in the vernacular, see Philo of Byzantium and Prager, Pneumatica. For convincing considerations concerning the authenticity of the Arabic version, see M.J.T. *Lewis, Millstone and Hammer*. *The Origins of Water Power* (Hull: The University of Hull, 1997). As it is certain that Philo's work on pneumatics was fundamentally influenced by the work of Ctesibius, of which however no work survived, it might be circumstantially inferred that such conception of the constitution of the elements was already stated by Ctesibius as well.

turn, had almost certainly derived them from Strato of Lampsacus.[15] Strato, whose intellectual provenience as head of the Lyceum in Athens is the Aristotelian philosophical tradition, unified the theoretical perspectives of Aristotelian physics with conceptions developed in the framework of atomism and formulated the idea that the elements are constituted of particles separated from each other by interstitial vacua. Hermann Diels has convincingly argued that such new physics of elements have to be understood in the frame of the realism diffused during the reign of Alexander the Great. This caused the emergence of a kind of empiricism, *ante litteram*, which is very well reflected in the treatises on pneumatics produced during the Hellenistic period.

According to this reconstruction, it becomes clear how Aristotle could have been confronted with similar ideas during his time, ideas that he attacked and tried to confute. In particular, Hero's principles are not in agreement with the Aristotelian doctrine, not only with respect to the principles of condensation and rarefaction but also, and especially, because of the supposed existence of interstitial vacua. Aristotle approached the problem in the following terms:

Some try to prove the existence of void from that of rarity and density.[16]

In his doctrine, Aristotle opposed the idea of existence of void in that which is rarefied. According to his doctrine, matter potentially has all the qualities such as rarity, density, heaviness, lightness, and so on. In fact, matter does not change:

[…] if air contracts or expands, the matter which is potentially smaller or larger becomes either the one or the other. For as the same matter from

[15] According to Hermann Diels, the conception of Strato was first developed by Erasistratus, a pupil of Theophrastus. See, Hermann Alexander Diels, "Über das physikalische System des Straton," *Sitzungsberichte der Königlich Preussischen Akademie der Wissenschaften zu Berlin*, 1893, 1, pp. 101–127.
[16] Aristotle and W.D. Ross*, Aristotle's Physics* (Oxford: Clarendon Press, 1960), 216b22.

being cold becomes hot or vice versa, so from being hot it becomes hotter, though nothing in the matter has become hot which was not already hot.[17]

These words refer to the principles of condensation and rarefaction, as described in *Aristotle's Meteorology*. Condensation and rarefaction are processes on whose basis natural motions take place.[18] They take place when matter, which exists in a particular form, changes into another form, for example, when water changes into vapor. The extension of the 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 vapor. 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 rarefaction of matter. The rarefied body becomes lighter than the body from which it originated and this is the reason why it eventually moves upward. The process of condensation works in the opposite way. Any process of rarefaction is accompanied by an increase in temperature, and processes of condensation with a decrease. According to Aristotle, condensation and rarefaction always involve a change of form, that is, a change of volume, of temperature, and of place. In these terms, the Aristotelian doctrine is also able to explain, at least seemingly, the functioning of pneumatic devices.

Apart from the existence of a sort of vacuum, Hero's doctrine seems to disagree with Aristotle's, especially because of the need to introduce the possibility of air contraction and expansion in relation to changes of temperature caused by a heat source.

This aspect easily leads to a comparison between Hero's and Aristotele's principles of condensation and rarefaction, for many characteristics these principles are in fact similar. When the Heronian interstitial vacua change their dimensions, a change of temperature, a change of extension of the volume, and a motion take place, as in the case of the Aristotelian rarefaction. The only difference is that Hero does not introduce the distinction between form and matter, which means that when all the changes that have been mentioned take place, there is no change of form, for instance of water into air or viceversa. The contraction of air is, according to Aristotle, an aspect of the more general process of condensation, which causes a body to change its form. If this solution was still absolutely convincing in reference to meteorological phenomena

[17] Ibid. (cit. note 16), 217a31.
[18] For the processes of condensation and rarefaction, see Aristotle, "Meteorologica," in Aristotle in *Twenty-Three Volumes*, edited by George P. Goold, Loeb Classical Library (Cam-bridge, MA: The Loeb Classical Library, 1987), 369a10–369b3.

such as the rain cycle, it was insufficient, however, to explain the phenomena mentioned and observed by Heron in his devices, where no transformation of elements could be observed.

Moving to the early modern period, as is well known, the Aristotelian doctrine was the dominant school of natural philosophy. Although its metaphysical character had been radically changed during the process of its integration with the Christian dogma during the 13th century, the scientific debate concerning the principles of rarefaction and condensation did not radically change the fundamental understanding of them, at least until the ancient work on pneumatics of Hero of Alexandria began to be widely diffused toward the end of the sixteenth century.[19]

2 The Early Modern Edition History of Hero's *Pneumatics*

Hero's text on pneumatics circulated until the end of the sixteenth century in manuscript form, mainly in Greek.[20] In 1575, the first printed edition of the Latin translation appeared which Federico Commandino, a mathematician at the court of Urbino,[21] had accomplished.[22] He realized many translations and

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[19] For the sake of completeness, it has to be added that the subject had already been discussed once, shortly before Commandino's work was printed and precisely by Girolamo Cardano in his *De Subtilitate*, published for the first time in 1550 and, after a profound revision, again in 1560. Cardano, who certainly had at his disposal a manuscript of Hero's *Pneumatics*, had already recognized the profound inconsistency between Hero's and Aristotle's theoretical approaches. Remaining within the Aristotelian frame, however, Cardano sought a solution by extending the meaning of Aristotle's distinction between form and matter and by contemplating that the form of the element could change so that their extension and volume could increase or decrease without resulting in a process of transformation of one element into another. According to the most recent interpreter of Cardano's theories – Elio Nenci – Cardano postulated that the volume of the element can range between a minimal and maximal extension without implying a change of forms, that is of substance, and of matter. For more details, see the introduction and *the First Book* of Girolamo Cardano, *De Subtilitate*, edited by Elio Nenci (Milano: Franco Angeli, 2004).

[20] For a reconstruction of the early modern reception history of Hero's Pneumatics in Greek, see Oreste Trabucco, "*L'opere stupende dell'arti piu ingegnose*" (Firenze: Leo S. Olschki, 2008).

[21] A fine study of the late Renaissance scientific milieu in Urbino is Enrico Gamba and Vico Montebelli, Le scienze a Urbino nel tardo Rinascimento (Urbino: Quattro Venti, 1988).

[22] Hero of Alexandria and Federico Commandino, *Heronis Alexandrini spiritalium liber* (Urbini: s.t., 1575).

prints of a large number of ancient scientific works. His translation of Hero's *Pneumatics* was published posthumously because Commandino had not yet finished revising his work before he died. For this reason his contemporaries found many passages in the text, which is now considered *editio princeps*, to be obscure and convoluted. Even Galileo criticized it in a letter to his friend Alvise Mocenigo in 1594.[23] The difficulty in understanding Commandino's text was the main reason that prompted Alessandrino Giorgi to produce his own translation of the Latin into Italian, which was published in 1592.[24] This version was much more comprehensible due to the annotations and comments he added. Of particular relevance concerning the early modern reception history of Hero's *Pneumatics* are the events that occurred between the publication of *editio princeps* in 1575 and its Italian translation in 1592.

In particular, in 1582 two further Italian editions were prepared. The first edition of the entire work – translated, commented, and enlarged – was accomplished by Oreste Vannocci Biringuccio[25] but never published. The second one was prepared by Bernardo Davanzati, who translated only the first part of the work, namely Hero's theoretical explanation, which was first published in 1863.[26] Oreste Vannocci Biringuccio was taught by his uncle, the engineer commonly known as Vannocci Biringuccio, famous for his work on metallurgy.[27] While Biringuccio was translating Hero's work, he also published the Italian translation of Piccolomini's commentary on Aristotle's *Mechanical Questions*.[28] Biringuccio's translation of *Pneumatics* is preserved in the form of a manuscript. In his introduction, Biringuccio explained that he not only used

[23] Letter from Galileo to Alvise Mocenigo, 11 January 1594, in Galileo Galilei and Antonio Favaro, *Le opere di Galileo Galilei,* 4th. ed., 20 vols. (Firenze: Giunti Barbèra Editore, 1968), Vol. X, pp. 64–65.

[24] Alessandro Giorgi, *Spiritali di Herrone alessandrino* (Urbino: Appressso Bartholomeo e Simone Rag, 1592). Alessandrino Giorgi requested and obtained permission to work with the same printer who had arranged the publication of Commandino's translation and re-used the same engravings.

[25] Hero of Alexandria and Oreste Vannocci Biringuccio, "Libro degli artifizii spiritali over di fiato d'Herone Alessandrino," in *Ms. L. VI. 44* (Siena: Biblioteca degli Intronati, 1582; reprint, Electronic edition by the Max Planck Institute for the History of Science. http://echo.mpiwg-berlin.mpg.de/content/pratolino/sources) (accessed 12 August 2013).

[26] Hero of Alexandria et al., *Della natura del voto di Erone Alessandrino. Volgarizzamento inedito di Bernardo Davanzati* (Roma: Tipografia delle Belle Arti, 1863).

[27] Vanoccio Biringuccio*, De la pirotechnia* (Venetia: Rossinello, 1540; reprint, edited by Adriano Carugo, Edizioni Il Polifilo, Milano, 1977).

[28] Alessandro Piccolomini and Oreste Vannocci Biringuccio, *Parafrasi di Monsignor Alessandro Piccolomini Arcivescovo di Patras, sopra le mecaniche d'Aristotile* (Roma: Zanetti, 1582).

the Latin translation of Commandino, but also a Greek manuscript that he found in the archives of the Vatican. From the Greek manuscript Biringuccio translated the description of "the fourth way to let the animals drink,"[29] a pneumatic device designed to create the illusion of a bird drinking water. At the end of the manuscript, he also added a description of a contemporary hydraulic organ, which he had seen in action in the garden of Tivoli.[30]

After Biringuccio's manuscript was produced, Giovanni Battista Aleotti, hydraulic-engineer for the Estensi at the Court in Ferrara, published a commented and enlarged Italian translation in 1589.[31] His translation of Hero's Pneumatics was made on the basis, he stated, of a Latin and a Greek text, without specifying which texts he actually used. Due to its prominence, however, it is easy to infer that he used Commandino's *editio princeps* for the Latin translation, whereas the Greek one remains unknown. Aleotti's translation was republished several times and in several languages during the following fifteen years. The descriptions and the illustrations of some of the new pneumatic devices that Aleotti added to his work were translated into Latin and republished several times until the end of the 17th century.

During the sixteenth century an Italian translation did not differ from a Latin version because it could reach a larger audience. At that time an Italian text could reach a *different* audience and, specifically, readers who were not exclusively interested in the ancient and scientific aspects of the ancient text, but also, and mainly, because they were interested in the practical implications, possible applications and projects. A reader of this type wanted to learn about the technological developments of antiquity in an instrumental way: for inspiration, ideas and solutions for his own ambitions and projects. The immediate attention paid to Hero's text and to the numerous translations in Italian that followed testify to a particular interest, primarily for the practical suggestions offered by Hero's descriptions of devices.

Within this context, the first peculiarity is that both of the first two Italian translations of 1582 were made at the request of Bernardo Buontalenti, one of the chief engineers at the Court in Florence at that time.[32] Buontalenti became particularly famous as a military architect owing to the numerous

[29] Hero of Alexandria and Vannocci Biringuccio, "Libro degli artifizii spiritali over di fiato d'Herone Alessandrino" (cit. note 25), fol. 2r.
[30] Ibid. (cit. note 25), fol. 70r–75r.
[31] Hero of Alexandria and Giovanni Battista Aleotti, *Gli artifitiosi et curiosi moti spiritali di Herrone* (Ferrara: per Vittorio Baldini, 1589).
[32] Hero of Alexandria and Vannocci Biringuccio, "Libro degli artifizii spiritali over di fiato d'Herone Alessandrino" (cit. note 25), fol. 1r.

fortresses he designed and whose building sites he coordinated. But he was also known as a machine maker, painter, builder of theatrical machinery, and hydraulic engineer. Furthermore, he is the author of many technical and artistic productions of the Florentine Renaissance. In 1569 Buontalenti was in charge of designing the villa and the garden of Pratolino together with the Grand Duke Francesco I. When the villa was completed around 1580, the work on its garden began. It is at this time that Buontalenti asked Biringuccio and Davanzati to translate Hero's *Pneumatics*.

3 The Garden of Pratolino

The land for the garden of Pratolino, located around twelve kilometers northeast of Florence in the direction of Bologna, was purchased in 1568 and the construction of its first building – the Grand Duke's villa – began in 1570. Construction in the park continued through the end of the century, well after the death of Francesco I, but continued to be supervised by Buontalenti.

In a basrelief by Giambologna dated to the late 1570s, one can see the same Giambologna offering a model of a fountain to Francesco I. Bonaventura da Orvieto, an automatamaker, and Bernardo Buontalenti are also depicted offering Buontalenti a model of the villa of Pratolino which was later built in the center of the garden.[33] The Grand Duke Francesco I (1541–1587) went down in history as a harsh, melancholic person dominated by desires of the flesh. In reality he was an intelligent and educated man who was interested in studying and not disdainful of the applied arts. Francesco spoke Italian in the Tuscan form that was sanctioned thanks to him (he founded the Accademia della Crusca in 1582) as well as Spanish, French, and German. He was also well versed in Latin and Ancient Greek. He was a great benefactor of academies and universities and his protégés included several philosophers and literati, such as Domenico Mellini and the already mentioned Bernardo Davanzati.[34]

In his famous work – *L'antirinascimento* – Eugenio Battisti portrays Francesco I as the Dux mechanicus, a figure similar to those evoked by Francis Bacon

[33] For an analysis of the bas-relief, see Detlef Heikamp, "Pratolino nei suoi giorni splendidi," *Antichità viva*, 1969, VIII:2, pp. 14–34.

[34] The most complete biographical work on Francesco I is Luciano Berti*, Il principe dello studiolo: Francesco I dei Medici e la fine del Rinascimento fiorentino, Varianti* (Pistoia: M&M, 2002).

in *his New Atlantis*.[35] Francesco was extremely interested in the work of the ducal workshops, which were dedicated mainly to pharmaceutics, alchemy, and metallurgy. In 1574, the workshops were relocated to the Fonderia al Casino di S. Marco, where Buontalenti had been working since he was fifteen years old, and where he gave lessons to the then nine-year-old Francesco.

Bernardo Buontalenti (1536–1608), an orphan, was raised and educated at the expense of the Florentine court. From the beginning of his career he worked mainly on architecture, in particular on military structures. A designer and builder of machines, famous for his theatre sets, a painter, civil architect, and hydraulic engineer, Buontalenti holds a place of honor in the history of the Grand Duchy of Tuscany and in the history of technology in general, especially during the latter half of the sixteenth century.[36] Recent and exhaustive studies define Buontalenti as the early modern Hero of Alexandria, as this work will also show.[37] Francesco I and Buontalenti became outstanding figures on the cultural scene of late sixteenth-century Florence. They were friends and shared a fascination for science and technology and, together, they conceived and created the garden of Pratolino.[38]

[35] Eugenio Battisti, *L'antirinascimento: con un'appendice di testi inediti,* 1. ed., Strumenti di studio (Milano: Garzanti, 1989), pp. 266–277.

[36] Amelio Fara dedicated up to four works to Buontalenti's life and work: Amelio Fara, ed. *Buontalenti, architettura e teatro (Firenze: La nuova Italia, 1979), Amelio Fara, Bernardo Buontalenti: l'architettura, la guerra e l'elemento geometrico*, Città, difese e architettura (Genova: Sagep, 1988), Amelio Fara, *Bernardo Buontalenti* (Milano: Electa, 1995), Amelio Fara, *Bernardo Buontalenti e Firenze: archittetura e disegno dal 1576 al 1607* (Firenze: Olschki, 1998).

[37] For an interpretation of Buontalenti's work as resembling that of an early modern Hero of Alexandria, see Luigi Zangheri*, Storia del giardino e del paesaggio: il verde nella cultura occidentale,* Giardini e paesaggio 6 (Firenze: Leo S. Olschki, 2003).

[38] There is a massive body of literature concerning the history of the garden of Pratolino. Due to their full coverage of the subject and historical sources, the texts that deserve mention above all others are Luigi Ulivieri and Simonetta Merendoni (eds.), *Pratolino, un mito alle porte di Firenze – Pratolino, a Myth at the Gates of Florence* (Venezia: Marsilio, 2009), *Luigi Zangheri, Pratolino, il giardino delle meraviglie, 2 vols.,* Documenti inediti di cultura toscana (Firenze: Gonnelli, 1987). The six texts in the series published by the *Ente Provincia di Firenze*, now owner of the garden, are also very significant: Marco Dezzi Bardeschi (ed.), *Il ritorno di Pan. Ricerche e progetti per il futuro di Pratolino, Pratolino.* Laboratorio di meraviglie (Firenze: Alinea Editrice, 1985), *La fonte delle fonti. Iconologia degli artifizi d'acqua. Pratolino. Laboratorio di meraviglie* (Firenze: Alinea Editrice, 1985), *Il concerto di statue. Pratolino. Laboratorio di meraviglie* (Firenze: Alinea Editrice, 1986), *Il giardino romantico. Pratolino. Laboratorio di meraviglie* (Firenze: Alinea Editrice, 1986), *Pratolino tra passato e presente.* Pratolino. Laboratorio di meraviglie (Firenze: Alinea Editrice, 1999).

According to the history of architectural landscape, from the sixteenth cen-tury on, Renaissance gardens were traditionally considered to be places where higher morality could be achieved.[39] A garden, whether located within a city or in the countryside, was an ideal place where rules different to those valid outside its boundaries were in force. Renaissance gardens were conceived to "work" unvaryingly and independently of the rhythm of the seasons.[40] Renaissance gardens, finally, became the place for the realization of Leon Battista Alberti's conception of grotesque during the sixteenth century: Their grottos became the most fundamental architectonic element after the implementation of this idea in the gardens of Boboli (Florence) and Pratolino.[41]

The way to create a garden that was to be considered and perceived as a place devoted to moral education was to build it according to an iconological program. The iconological deciphering of the garden of Pratolino has been the subject of several studies and researches,[42] though these are by no means conclusive.

Certainly water played the most relevant role in the process of realization of the iconological program of the garden. The garden indeed included a large number of water tricks, fountains, and groups of water-powered automata. It could symbolize the difficulties, hazards, and uncertainties encountered

[39] The moral command of the Florentine humanists was to improve the moral and physical world, and the realization of a garden was one of the possible means at disposal to accomplish such a command. For more details, see Eugenio Battisti, *Iconologia ed ecologia del giardino e del paesaggio,* Giardini e paesaggio (Firenze: L.S. Olschki, 2004), p. 11, 48.

[40] A fascinating introduction to the meaning of early modern gardens is in ibid. (cit. note 39), pp. 3–51, 267–279.

[41] Zangheri, *Storia del giardino e del paesaggio: il verde nella cultura occidentale* (cit. note 37), p. 44.

[42] For the most significant works devoted to the investigation of the iconological program of the garden of Pratolino, see Matteo Valleriani, "The Garden of Pratolino: Ancient Technology Breaks Through the Barriers of Modern Iconology," in *Ludi Naturae – Spiele der Natur. Transformationen eines antiken Topos in Wissenschaft und Kunst*, edited by Natascha Adamowsky, Robert Felfe, and Hartmut Böhme (München: Fink Verlag, 2010), pp. 120–141, Marco Dezzi Bardeschi, "Il gran teatro arcano di Pratolino," in *Il ritorno di Pan. Ricerche e progetti per il futuro di Pratolino*, edited by Marco Dezzi Bardeschi, Pratolino. Laboratorio di Meraviglie (Firenze: Alinea Editrice, 1985), pp. 13–30, Zangheri, *Pratolino, il giardino delle meraviglie* (cit. note 38), pp. 21–41, Luigi Zangheri, *Storia del giardino e del paesaggio: il verde nella cultura occidentale* (cit. note 37), pp. 33–50, 275–343, Luigi Zangheri, "Per una lettura iconologica di Pratolino," *Antichità viva*, 1977, 16:4, pp. 30–34, Eugenio Battisti, *Iconologia ed ecologia del giardino e del paesaggio* (cit. note 39), pp. 3–50, 267–290, Eugenio Battisti, *L'antirinascimento: con un'appendice di testi inediti* (cit. note 35), pp. 249–286.

en route to the elevation of the human intellect. In order to take on this important role in the garden's dynamics, the water first of all had to be tamed and controlled. It is at this point that the use of pneumatic technology found its *raison d'être* and point of pride: technical experts, engineers and constructors worked together in the service of a cultural project aiming to strengthen human rationality in harmony with nature.

Pratolino comprises two levels: the exterior surface of the garden visible to all and the concealed underground section. Beneath the garden was an enormous hydraulic laboratory with numerous grottoes, keys, vats, valves, pipes, and passageways. This was certainly planned from the beginning and built from 1568 on, just before the construction of the villa began in 1570. The hydraulic and pneumatic technology at Pratolino represents the highest level reached in these fields during the sixteenth century. According to engineers' reports, in Pratolino up to 172 keys were counted that activated and deactivated devices.[43] These were located along kilometers of a subterranean aqueduct, which, surprisingly for the time, were not built on the basis of simple geometrical shapes and according to economic constraints, but rather followed paths without any apparent order.[44]

As will be shown in the following, however, the peculiarity of the garden of Pratolino was not represented by the extensive use of pneumatic devices – this had already been realized for instance in the garden of Tivoli – but especially by the fact that such devices were inspired by the diffusion of Hero's *Pneumatics*.

At the end of the sixteenth century, pneumatics was in fact a flourishing practical activity cultivated by many engineers, especially at the courts. Pneumatics in the Renaissance represented a fundamental discipline, which, in combination with hydraulics, enabled engineers to create water supply systems and fluvial networks in order to supply entire cities and to power a great number of mills. An impressive example for the relevance of pneumatics during the Renaissance is represented by the project of prolongation of the Secchia canal in the region of the Italian city Reggio Emilia during the first half of the fifteenth century. As Massimo Mussini showed,[45] the canal was prolonged by

[43] Zangheri, *Pratolino, il giardino delle meraviglie* (cit. note 38), pp. 139–142.

[44] According to the spirit of the time, water technology had to order its iconological effect as if this were nature acting in the garden. A perfect imitation of nature was therefore required. For this reason the underground aqueduct could not be built symmetrically or just following the shortest paths, because the water effects connected to the aqueduct would not have been perceived as being natural.

[45] Massimo Mussini, "Governo delle acque nel territorio reggiano fra Medioevo e Rinascimento," in *La civiltà delle acque dal Medioevo al Rinascimento*, edited by Arturo Calzona and Daniela Lamberini (Firenze: Olschki, 2010), pp. 221–241.

twenty kilometers and in the process had to cross thirteen torrents. To cross the Tresinaro torrent, a 309,5-meter inverted syphon was built on the riverbed during the dry period. Not only was this kind of engineering feasible due to the experience of hydraulic engineers, but in addition it could only be realized if the professionals' background included practical pneumatics as well.

Practical pneumatics had been cultivated without interruption and with more or less the same intensity since antiquity. Starting from the time of the Comuni in Italy and with favorable economic conditions, largescale projects involving pneumatics gave rise to an impressive accumulation of experience and skill in this field. It is within this frame that ancient pneumatics, in the form of the editions of Hero's work, reappeared at the end of the sixteenth century.

4 The Water Technology of the Garden of Pratolino

In the actual garden of Pratolino virtually nothing is left of the pneumatic apparatuses that were built. Because of the construction materials used, the devices disappeared over time. What remained was then eventually taken out in later epochs in order to re-adapt the garden to new tastes and styles.

Due to the grandiosity of the entire technological system, however, Pratolino became an attraction all over Europe. For this reason, numerous textual sources and drawings have been preserved which allow for a punctual reconstruction of almost all the devices that were designed and constructed between the end of the sixteenth and the beginning of the seventeenth century. The high maintenance requirements of both the hydraulic system and of the apparatuses, moreover, obliged the Tuscan administration to continuously supervise and intervene. Consequently, a great number of documents of administrative character are still at disposal in the archives.[46]

[46] The Provincia di Firenze and the author of the present work curated a digital library of the sources thanks to the support of the State Archive of Florence, the Biblioteca Moreniana and Riccardiana also in Florence, to the National Library of Florence, the Biblioteca degli Intronati di Siena, The Humboldt-Universität in Berlin, the Eidgenössische Technische Hochschule in Zürich, and the Albertina in Vienna. The library is hosted in the frame-work of the project ECHO: http://echo.mpiwg-berlin.mpg.de/content/pratolino (accessed 7 August 2013). The virtual reconstruction of the garden (cit. note 52) is linked to the digital library as well.

A very systematic description of many pneumatic devices built in Pratolino is represented by an anonymous text preserved at the Biblioteca Riccardiana.[47] Relevant illustrative materials are provided by the engravings of Stefano della Bella[48] and by the work of Giovanni Guerra, who was charged by Pope Innocent IX to travel throughout Europe to prepare drawings of the most beautiful "things" he could find.[49] A further extremely relevant source, which provides technical drawings commented in marginal notes in texts, are a series of folios of Wilhelm Schickhardt's manuscript entitled *Zweite italienische Reise*, compiled in 1600 and now preserved in Stuttgart.[50]

In 1600 the German engineer Heinrich Schickhardt visited Pratolino[51] and by reconstructing part of his trip, it is possible to offer an idea of the technology employed at Pratolino.[52] Under the villa of the Grand Duke were two levels of grottos where different mechanical devices could be admired. On one level was a grotto with twosided automata systems. One of these systems represented the god Pan. These are neither paintings nor statues, but rather very large automata. The best description of what a visitor could see, in line with the plans of Francesco I, was written by Da Prato, who wrote a celebratory text for the Demidoff family, later owner of the garden, published in 1886:

This second grotto is the fountain of Pan. The divinity is portrayed by a statue seated on reeds; it stands up, moves its head and turns its eyes; in its hands it holds a *zampogna* [bagpipe] with seven holes and plays it like a master, to the great amusement of the listeners, causing the people above to dance; after displaying its talent it sits down and gazes at a woman near to him. She is the nymph Syrinx who, annoyed at being stared at by the magical musician, transforms herself into a tuft of reeds and spouts a stream of clear water. Amidst all these changes, a cuckoo rises from

[47] "Descrizione dei giochi d'acqua di Pratolino," (Biblioteca Riccardiana, end of the sixteenth century), ms. 2312.
[48] Stefano della Bella's engravings are published in Bernardo Sansone Sgrilli*, Descrizione della regia villa, fontane, e fabbriche di Pratolino* (Firenze: Per Tartini e Franchi, stamperia granducale, 1742).
[49] Giovanni Guerra, "Disegni di Giovanni Guerra," (Vienna: Albertina, 1598), Architektur, Graphische Sammlung, fol. 37197–37235.
[50] Heinrich Schickhardt, "Zweite italienische Reise," (Stuttgart: Württembergische Landes-bibliothek, 1600), Cod. Hist. 4, ms. 148.
[51] Ibid. (cit. note 50).
[52] A virtual tour through the garden of Pratolino with access to sixteenth-century historical sources is provided at http://pratolino.mpiwg-berlin.mpg.de (accessed 12 August 2013).

the fronds that are part of the decoration and starts to sing a sweet song. Listening to the cuckoo's song one wants to see where it is, and our eyes can see the other beauties of the grotto, from the half-barrel vaults […].[53]

These effects did not overly impress Heinrich Schickhardt. Certainly, the cuckoo aroused his curiosity since he was not able to identify the source. The cuckoo was a scenic artifice which forced visitors to turn their eyes elsewhere and perhaps encounter the gaze of others. However, Schickhardt decided to continue and go around to the back to discover the secret of the cuckoo. The engine room of the Grotto of Pan still exists today. An excerpt from a report, most probably written by Giuseppe Ruggieri in 1757 and which is conserved in the State Archives of Prague, gives an idea of what was operating in this engine room:

Behind the statue of Mugnone inside the Grotto of Pan is a small cistern that takes the overflow from a larger one and leads it to a small vat marked 66, where the pipe divides into two branches that bring the water to the cisterns of the Fountain-Alley […]. In the chambers beneath the Grotto of Pan are six keys; one is used to fill the drum to activate the statue of the satyr [Pan stands up], one to produce the wind for the instrument he holds in his hands [the seven-holes pipe], one to empty the drum [Pan sits down], one to send water to the statue of Syrinx [the nymph Syrinx is transformed into a tuft of reeds that spouts water], one to fill the drum that makes the cuckoo sing and one to empty the cuckoo's drum.[54]

This engine room could only be reached via secret passageways behind the Grotto of Pan. The hydraulic system and pneumatic devices were not in constant operation in the garden of Pratolino. There were a great number of keys, bearings, and valves along the underground passageways and a team of plumbers on hand to activate them. When visitors walked around Pratolino, the plumbers moved with them, but remained unseen. According to Francesco I's concept, the tour of the garden had to be meticulously planned in advance.

[53] Cesare da Prato, *Firenze ai Demidoff. Pratolino e S. Donato. Relazione storica e descrittiva preceduta da cenni biografici sui Demidoff* (Firenze: Tipografia della Pia Casa di Patronato per minorenni, 1886), pp. 260–261. Stefano della Bella produced an engraving of the Grotto of the God Pan: see, Sgrilli, *Descrizione della regia villa, fontane, e fabbriche di Pratolino* (cit. note 48), unnumbered table.
[54] Lorraine Archive, Pietro Leopoldo, Piante dei condotti, c. 20r and cc. 25r–25v.

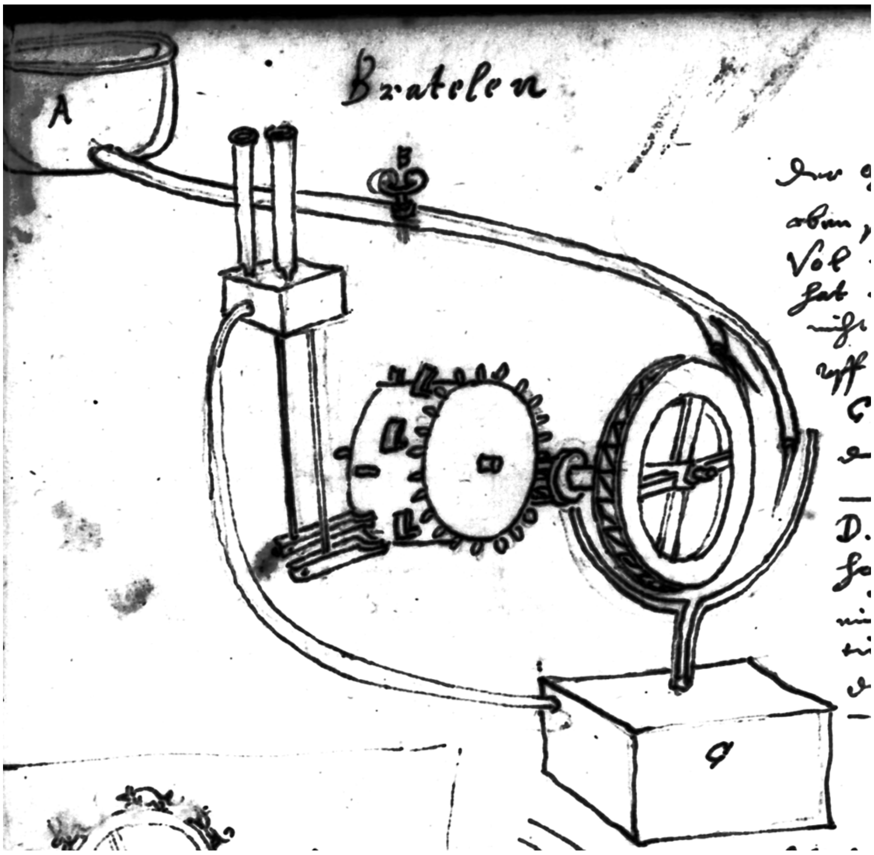

Figure 1 *Heinrich Schickhardt's drawing of a cuckoo machine built in the garden of Pratolino. From Heinrich Schickhardt, Zweite italienische Reise, Stuttgart, Württembergische Landesbibliothek, Cod. hist. qt. 148, Bl. 52r.*

Schickhardt probably went through this passageway on his way to the engine room of the Grotto of Pan. In his notes, Schickhardt sketched a machine that created the cuckoo's song (Fig. 1),[55] which he then described as follows:

[55] Schickhardt located the cuckoo inside the Grotto of the Samaritan where several machines were set up to reproduce the songs of several birds. Other sources, however, raise doubts as to whether there was a machine to reproduce the cuckoo's sound in the Grotto of the Samaritan. However, since the machines were similar, it is not difficult to assume that the machine inside the engine room of the Grotto of Pan making the sound of the cuckoo was identical to the one sketched by Schickhardt.

This text was published on page 145 of the article "Ancient pneumatics transformed during the early modern period.".

At the top there is a container A filled with water. It has a feed cock B so that neither too much nor too little water goes onto the wheel and into container C (that sends the air into the pipes).[56]

The two keys relative to the cuckoo, as described in the Lorraine Archive in Prague, served to fill container A and to drain container C at the end of each performance.[57] Feed cock B was not a key, but most probably a valve that served to regulate the flow but not to stop it. Without a theory of water flow and the possibility of applying it to a specific mechanism, the Renaissance engineer's method was first to build the device and then to adjust it. The constructors constructed the machine so that it could be made to work using just one valve, which implies that the experience provided the minimum and maximum conditions for the machine's operation. The other components of the machine were: 1) a waterwheel which was evidently made in the manner of the old water mills insofar as the shape and angle of the paddles and their delivery were concerned; 2) an overshot pouring the water onto the paddles; 3) a camshaft which, through a transmission mechanism, opened and closed the probably pistonshaped valves situated beneath the two organ pipes and inside a small sealed container for the air; 4) two gears for transmitting drive from the waterwheel to the camshaft. The first gear had a horizontal axle positioned at the center and terminated in a gear that was known as the widely used spindle. The second one was positioned and built directly on top of the camshaft. This gear offered another way of adjusting the speed of the machine and hence the cuckoo's melody and its duration.
The water coming from container A was diverted into two pipes. The first threw water on the waterwheel paddles and the second led the water into container C, which was connected directly to the organ pipes supplying the air pushed out of container C by filling it with water. This machine must have reached a certain level of standardization, at least at Pratolino, since there was no provision for a valve to regulate the water flow after the pipe branched. In fact, this would have made it possible to adjust the machine for the melody to be played more slowly and loudly, or faster and more softly.

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[56] Schickhardt, "Zweite italienische Reise" (cit. note 50), fol. b–52r.
[57] The following analysis is also based on the research results of research by Marcus Popplow and Wolfgang Lefévre, who conducted a study on hundreds of Renaissance machines, including some of Schickhardt's. These results can be accessed via the Web por-tal "Database Machine Drawings" at http://dmd.mpiwg-berlin.mpg.de (accessed 12 August 2013).

As for the materials, the organ pipes were almost certainly made of lead, as was customary at the time.[58] The entire drive mechanism was made of wood, like the camshaft. Containers A and C were probably made of copper, since other containers and large parts of other machines were also made of copper, as described by Schickhardt.[59] Valve B was certainly metal, but it is difficult to determine whether it was iron or bronze. The pipes could have been made of lead or copper since no other material would have been able to function appropriately for this purpose. Most probably they were made of copper. Even at low temperatures and using simple techniques, it was already possible to weld the copper pipes to the containers. One technique was to cut a smaller opening than the diameter of the pipe into the container; the copper around the opening was heated, then the pipe was inserted under pressure and held fast in the desired position until it cooled down.

Although the cuckoo is one of the less elaborated machines realized at the garden of Pratolino, it already clearly shows the level of specialization of the artisans who were at work under the supervision of Buontalenti.

Among the numerous other realizations in the field of hydraulics and pneumatics, moreover, there was space and ease to carry on a peculiar process, which had never happened in such a systematic way before. This process can be defined as the material translation of Hero's work.

5 Pratolino as a Workbench for Heronian Pneumantic Devices

A comparison between the sources concerned with the pneumatics devices built in the garden and those described in Hero's work, shows that Buontalenti, who requested the Italian translation of the text, indeed used this work as a source while supervising and commanding the construction of the garden. Heronian influence on the system of pneumatic apparatuses in the garden

[58] The study of materials and how they are processed is based on the results published in 2006 following a reconstruction of the "Galatea" water organ described by Salomon de Caus in 1615 in *Les raisons des forces mouvantes avec diverses machines* (Frankfurt a. M.: Abraham Bacquart, 1615). For more details, see the contributions by Hans Holländer, Yves Weinand and Guido Schumacher in Boje E. Schmuhl and Ute Omonsky (eds.), *Maschinen und Mechanismen in der Musik. Sammelband zur XXXI. Wissenschaftliche Arbeitstagung Michaelstein* (Augsburg: Wissner, 2006).

[59] The use of copper is confirmed by Schickhardt, for example in Schickhardt, "Zweite italienische Reise" (cit. note 50), fol. b–50r.

of Pratolino can be detected on three different levels: aesthetics, design and composition, and technology.
Concerning the aesthetics and because no illustration of ancient pneumatic devices was known in the early modern period, the comparison can obviously be made only between technological artifacts built in Pratolino and illustrative material, which, however, is dated to the early modern period as well. From this perspective, it is interesting to note that certain artifacts seem to replicate artifacts illustrated in the early modern *editio princeps of Hero's Pneumatics*.[60]
In front of the Grotto of Pan there was the grotto called of the Pheme.[61] In da Prato's words:

[…] the Pheme is at a high location and moves its wings. It has a gold trumpet in its hands, which is brought to its mouth and played loudly. Below it, there is a niche where a man with the aspect of a farmer is sitting close to a dragon. He is taking water by means of a cup, accomplishing the true and natural movement for it, and with that cup he waters the animal, which in turn bends down its head and drinks watching the cup.[62]

If the aspects related to pneumatics are extrapolated, the solution found for the Pratolino automata closely resembles Commandino's illustration of the playing trumpeter.[63] For the description of the technical pneumatic apparatus, Oreste Vannoccio Biringuccio's translation of this device can be used:

[…] one lets the trumpets play. If the pipe of the funnel is inserted into the closed recipient and not too far from the bottom, and then is sealed with its cap and a trumpet with its reed and the large pipe is in the mouth, perforated together with the recipient on its upper part, then it happens that, if the water is poured through the funnel, the air, which is inside, is pushed out through the trumpet and produces the sound.[64]

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[60] Hero of Alexandria and Commandino, Heronis Alexandrini spiritalium liber (cit. note 22).
[61] Stefano della Bella produced an engraving of the Grotto of the Pheme: see, Sgrilli, *Descrizione della regia villa, fontane, e fabbriche di Pratolino* (cit. note 48), unnumbered table.
[62] da Prato, *Firenze ai Demidoff* (cit note 53), pp. 259–260.
[63] Hero of Alexandria and Commandino, *Heronis Alexandrini spiritalium liber* (cit. note 22), Prop. 49, p. 51r.
[64] Hero of Alexandria and Vannocci Biringuccio, "Libro degli artifizii spiritali over di fiato d'Herone Alessandrino" (cit. note 25), fol. 31v–32r.

Biringuccio's manuscript is not provided with images, though placeholders were left to indicate to the typographers where the images had to be inserted. Biringuccio also stated in his dedicatory letter to Buontalenti that he had produced new images, different from the ones produced for Commandino's edition. Those images are now lost and it is impossible to know whether Buontalenti ever saw them. But the similarities between Commandino's pictorial rendering of the pneumatic trumpet (with trumpeter) and the solution found for the statue of the Pheme are evident. Certainly the influences of Hero's work on the conception of the pneumatic apparatuses of Pratolino, however, went beyond the consideration of aesthetic solutions found for the early modern editions of the treatise.

More decisive from this perspective is the recognition of the fact that proper Heronian machines were built in the garden. An evident example is the famous Heronian machine of the singing birds. Water is poured into the system from an external source, at which stage, four different birds begin to sing. Due to the pneumatic apparatus, at one point an owl turns toward the birds and these stop singing. This composition, which is probably the most renowned among the Heronian machines, was reproduced many times after the diffusion of Hero's Pneumatics in print form. Apparently, however, the first time this occurred was in Pratolino. According to Bernardo Sansone Sgrilli, the same machine was in operation over the door of the automata of the shepherdess in the Grotto of the Samaritan:

Over the door, or gate, from which the shepherdess exits, is an owl that turns towards the birds […].[65]

In the case of the bird machine, therefore, the Heronian suggestions are followed concerning design and composition, that is, the sequence of actions to be performed.

The artisans working on the construction of Pratolino not only had the chance to experience that the technical compositions suggested by Hero really worked, however, but also had the possibility to reflect upon his technology and to compare it with their own. This happened for instance in the case of the hydraulic organ. In the garden of Pratolino two hydraulic organs were built:

[65] Sgrilli, *Descrizione della regia villa, fontane, e fabbriche di Pratolino* (cit. note 48), p. 19. The same is reported in da Prato, *Firenze ai Demidoff* (cit. note 53), p. 255. The owl is visible in the following drawing of the Grotto of the Samaritan: Guerra, "Disegni di Giovanni Guerra" (cit. note 49), fol. 37214.

one in Mount Parnassus and another under the villa in one grotto. Both of them were hidden to visitors and conceived to perform mechanically.

Ancient hydraulic organs like the one suggested by Hero in his treatise[66] were conceived as musical instruments played by organists. During the Renaissance the organ played by musicians was no longer hydraulic, but rather Aeolic. The hydraulic organ found a new role in the context of complex hydraulic and pneumatic systems such as those in the gardens. Their purpose was simply the mechanical execution of a composition,[67] and as such they were operated by hydraulic mechanics. There was no need for a manual: this was substituted by a roller with small wooden blocks that mechanically operated devices to open and close the pipes. The machine no longer required a high degree of dynamism since it only had to open and close the pipes; a musician would have been able to look for intermediary solutions, learn them, and keep them in his store of experience.

The new context in which organs were used therefore led to some degree of simplification of the mechanisms adopted. But it was not just these mechanisms that were simplified: the development of the pneumatic apparatus was also certainly influenced by the new context. The compositions that the machine was now meant to perform were no longer potentially infinite in number. The machine was built and calibrated for a single musical purpose. In gardens, for instance, the mechanical hydraulic organ gave off sounds and/or a melody that represented a particular aspect of a precise allegorical and iconographic context. Together with other elements such as artworks, watergames, botanical compositions, and so on, these sounds contributed to the definition of a particular place and context in the garden.

Considering the organ built in the Mount Parnassus, its melody was meant to be heard as if played by the nine Muses, statues placed on top of the artificial mountain. Heinrich Schickhardt's description shows how simple the workings of this pneumatic machine actually were (Fig. 2):

This work plays only two pieces [compositions]. One, when the wheel has completed a halfturn, the other when it is found in the other half. The notes that the organ lets out are the principal and an octave [higher]. […] 35 wooden blocks […].[68]

[66] Hero of Alexandria, "Heronis Alexandrini pneumaticorum libri duo" (cit. note 8), pp. 192–202.
[67] For a very full introduction to Renaissance pneumatic musical instruments, see Schmuhl and Omonsky (eds.), *Maschinen und Mechanismen in der Musik* (cit. note 58).
[68] Schickhardt, "Zweite italienische Reise" (cit. note 50), fol. b–53r.

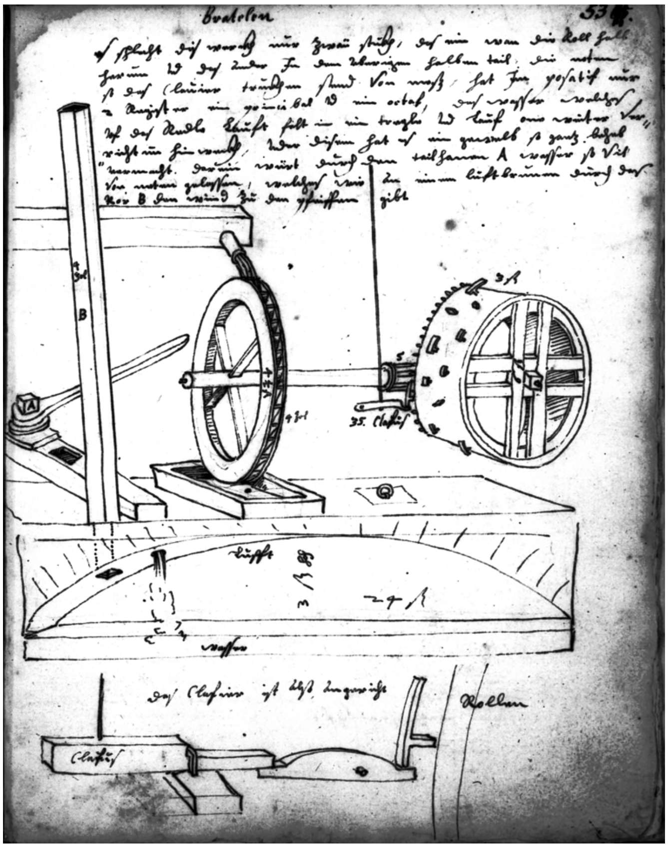

Figure 2 *Sketch of the pneumatic apparatus of the hydraulic organ of the Mount Parnassus at Pratolino. Heinrich Schickhardt, Zweite italienische Reise, Stuttgart, Württembergische Landesbibliothek, Cod. hist. qt. 148, Bl. 53r.*

The melody was very short, being composed of only 17 notes, and was repeated an octave higher. Adding a probable anacrusis, one arrives at the number of 35 wooden blocks counted by Schickhardt on the organ roller.

Once the melody and registers had been determined, the Renaissance hydraulic machine required a pneumatic apparatus that could play them with

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the desired intensity. After this was assured, however, there was no need for any other mechanism that would allow different compositions to be performed, possibly with different intensity or volume. This is probably why none of the known Renaissance hydraulic organs were equipped with pumps that could further increase the pressure in the air system.

An analysis of Schickhardt's notes and drawings shows that the pneumatic apparatus of the Pratolino water organ is fairly simple. The hydraulic systems that activated the pneumatic and mechanical apparatuses seem to have been separated, even if there was probably a common key to control the whole system. When this first key was opened, the mechanical apparatus started up immediately: the water wheel set the transmission mechanisms in motion; they then turned the roller with the nogs. This then opened and closed the organ pipes, which were probably located on top of the Mount (perhaps inside the statues of the muses), through the mechanism shown in Schickhardt's drawing at the bottom of the page. The pneumatic apparatus was then started up by another key, visible to the left of the water wheel. Opening this allowed water to flow into the basin drawn at the bottom. Subsequently, the water that had been introduced forced the air to escape through the tube drawn by Schickhardt near the key that started up the pneumatic apparatus. Finally, this tube brought the air to the organ pipes. Schickhardt described the pneumatic apparatus as follows:

The water that runs over the wheel arrives in a basin and flows away without other mechanisms. Below it, there is a very solid and closed vault. Opening key A, a great amount of water is introduced into this vault, as much water as is needed. The water then provides wind for the pipes through tube B as in a fountain of air.[69]

Compared to Hero's hydraulic organ (Fig. 3), the one in Mount Parnassus at Pratolino is of almost disarming simplicity. However, it is still possible to find a fundamental technical characteristic common to both. According to a specific interpretative hypothesis developed elsewhere,[70] the main pneumatic device of Hero's hydraulic organ was the system composed of the cylinder

[69] Ibid. (cit. note 50).

[70] For an analysis of Hero's hydraulic organ, in comparison to Vitruvius's description as well as their early modern reception, see Matteo Valleriani, "Il ruolo della pneumatica antica durante il Rinascimento: l'esempio dell'organo idraulico nel giardino di Pratolino," *in La civiltà delle acque dal Medioevo al Rinascimento*, edited by Arturo Calzona and Daniela Lamberini, Ingenium (Firenze: Olschki, 2010), pp. 613–632.

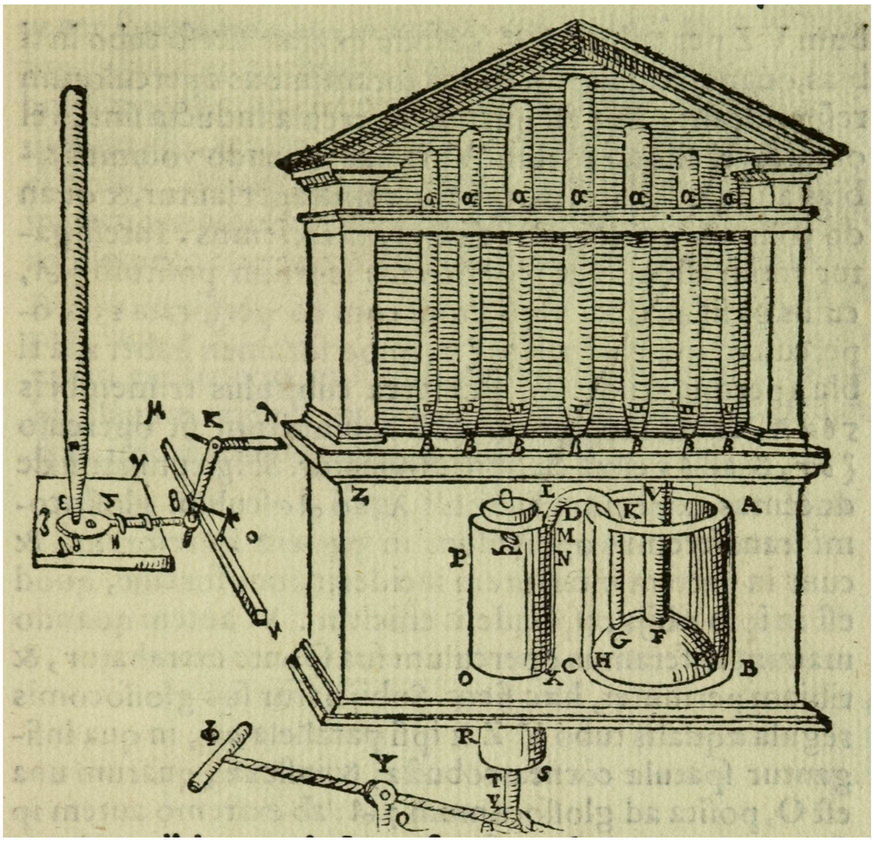

Figure 3 *Federico Commandino's interpretation of Hero's description of a hydraulic organ. From Federico Commandino, Heronis Alexandrini Spiritalium liber, Urbino, 1575, Prop. 55, pp. 76–77 (sometimes marked as p. 70 due to incorrect page numbering). Courtesy of the Library of the Max Planck Institute for the History of Science.*

hermetically closed at its top by the reversed vessel, which held the water, and thus differs from Commandino's interpretation. The pneumatic apparatus of the Pratolino organ is in fact made up of a cylinder and a reversed vessel, too, which, transferred into the real dimensions observed by Schickhardt, becomes a small, probably cylindrical basin and a "very solid" vault that seals it off perfectly.

While in Hero's organ it is air that is pumped in, in Pratolino the operation is based on the introduction of water. One fundamental consequence of this difference is that the quantity of air is depleted so the music can start again only after the basin has been emptied. Nonetheless, considering the water organs' new role in Renaissance, this characteristic did not present a limitation. The organ had to emit a certain mechanically created melody for a predefined timelapse. Based on this choice and on the amount of water to be introduced, the size and especially the capacity of the basin were decided.

The organ of the Mount Parnassus therefore also represents a reproduction of the Heronian apparatus, though revisited by the early modern professionals on the basis of their advanced experience. That their experience and skill were more than enough to properly understand Hero is also shown by the fact that the artisans at Pratolino, under the supervision of Buontalenti, chose to seal the cylinder by means of a choking vessel and not just a flat surface.[71] This aspect represents evidence of the superiority of early modern practical pneumatics in comparison to ancient pneumatics, at least in the way it is codified by Hero of Alexandria. The choking vessel is in fact a technical solution to avoid possible turbulence created by an increase of viscosity due to the increase of air pressure when water is poured into the system. Especially in pneumatic devices, whose function was to emit musical performances, turbulence could create sudden disturbing changes of peaks.

Pratolino's hydraulic organ, in conclusion, can be seen as a reproduction of Hero's pneumatic apparatus, but improved according to the contemporary technology. The artisans and engineers had had the chance to try and even almost manually test the technical suggestions put forward by the ancients, which can be considered a groundbreaking novelty in the cultural life of the period.

Relevant for this work is the fact that Heronian technical compositions and pneumatic apparatuses were reproduced in the garden of Pratolino and that the tests at the workbench turned out successfully.

One aspect that remains to be discussed is the fact that not all the machines in the garden were properly Heronian. Pratolino was Heronian but, at the same time, also more than this. This aspect was not only represented by the technical improvements such as the one mentioned in reference to the hydraulic organ. More and new devices had to be built as well and also more elaborated connections had to be made between the art of pneumatics and the art of automata, which is the other great chapter of Heronian science.

By means of an analysis of the way Pratolino was perceived outside, it can be demonstrated that Pratolino was considered Heronian to such an extent that even the new devices conceived for and built in the garden were considered to be Heronian art at the time.

[71] Ibid. (cit. note 70).

6 The Garden Percieved as Heronian

To show that Pratolino was considered a Heronian realization from its very beginning and that it was perceived as such from the outside, I will again consider the general iconological meaning of the garden of Pratolino and even some general cultural aspects of Florence of the Grand Duke Francesco, after first fully describing the Grotto of the Samaritan.

One of the six grottos of the first level under the villa in the garden, the Grotto of the Sponge, was constituted of three different rooms. From the technological point of view the last room, also called the Grotto of the Samaritan (Fig. 4), was particularly sophisticated. According to Sgrilli:

[…] one enters the Grotto of the Samaritan. In the middle there is a table with eight sides made of different kinds of marble. Each side has a hollowed oval in which the visitors can refresh themselves. In the middle of the table is a circle, similarly hollowed, from which a fountain originates. This displays several water tricks with shapes formed by means of ingenious devices. Close to this is a fullscale stone figure, which pours water from a vessel into a basin. Close to this and within a grotesque is a fortress with the tower in the middle, an invention of Ferdinando Tacca.[72] On its walls the combatants appear and pretend to defend it and with their muskets they fire against the aggressors. Although everything is artificial, the skill of the master is so well expressed in the work that the combatants seem to display vigor and fury at the same time. Similarly, one sees other soldiers who, pretending to attack the fortress, fire innumerable musket shots against the visitors [of the grotto]. At the same time many cannons are fired from the tower and from the walls, and one can hear a great roar of drums. From within this fortress a young shepherdess appears, the Samaritan. She enters through a selfopening gate, goes forth walking with a bucket in her hand which she fills when she arrives at the spring. Then she turns and goes back, moving her hand and waist appropriately

[72] Ferdinando Tacca was a technician, an expert in metalworking, bell-casting, and also a sculptor, but not to be confused with the more famous Ferdinando Tacca, a sculptor born in 1619. The technician Ferdinando Tacca, who built the automata fortress, is probably the same person with whom Galileo had a fruitful correspondence on the issue of bell-casting in 1633 during Galileo's stay in Siena after his abjuration. For more details, see Matteo Valleriani, "Galileo in the Role of the Caster's Assistant: The 1634 Bell of the Torre del Mangia in Siena," *Galileana*, 2008, 5, pp. 89–112.

This text was published on page 155 of the article "Ancient pneumatics transformed during the early modern period.".

Figure 4 *Giovanni Guerra, Prospettiva della Grotta della Samaritana, 1598, Architektur, Graphische Sammlung, Albertina, Vienna. no. 37214 (www.albertina.at).*

and marvelously. Once she has entered the gate, it closes. A shepherd, who stays close to the spring and observes this woman, fits perfectly to this action when he turns toward her and gently plays the bagpipes. On the walls, decorated with sponges, one sees two small houses filled with workshops; one of them, the socalled Forge of Vulcan, contains small figures working as smiths with anvils, hammers, iron tools and all they need for their art. Close to this is the building of the mill, where there is a figure with a sack on its shoulders, operating according to the needs of the mill. Finally, the millstone moves as well thanks to the force of the water. Far away, then, one notices a hunting scene with many hunters and animals, running after each other, and close to them there are other animals, among them two ducks which lower their heads and drink; before them, one sees some marvelous tricks, among them a snake that turns around and other animals and various species of trees, above which there are many birds that sing in many ways. Over the door, or gate, from which the shepherdess exits, there is an owl which moves towards the birds, and there are beautiful and stupendous things that one would need too long time to describe in their details and all of them are operated by the force of the water. The vault and the walls of these grottos are decorated with many sections, filled with stones of various colors, niches, motherofpearl objects, and many peculiar things. The hidden devices and the strange inventions directed towards the visitors and the most curious people who cannot avoid them, are so numerous and peculiar that it seems impossible that the human mind was able to imagine and realize them.[73]

According to the iconological program of the garden of Pratolino, the villa represented the highest peak of rationality and this was symbolized not only by the highest sophistication of the mechanical contrivances built in the grottos at the subterranean level, but also and especially by the iconographic meaning of such contrivances. Following Vergilian echoes,[74] war, which certainly is one of the most preeminent subjects in the grotto of the Samaritan, was highly prominent in the stairs of rationality.
Moreover, it is easy to conceive that Francesco I's alchemic culture framed the conception and the overarching meaning of the garden, too. The icono-

[73] Sgrilli, *Descrizione della regia villa, fontane, e fabbriche di Pratolino* (cit. note 48), pp. 17–19.
[74] Valleriani, "The Garden of Pratolino: Ancient Technology Breaks Through the Barriers of Modern Iconology" (cit. note 42).

logical program of the garden of Pratolino can in fact also be considered the projection of the program already represented in the *Studiolo* of Francesco I, where Prometheus receives quartz from Nature, and this corresponds to the subject of unification of art and nature realized by the capacity of the alchemist to let the elements transform into each other.[75] There were numerous alchemic themes within Pratolino, though they were sometimes kept hidden according to the same alchemic culture and also because of the spirit of the Counter Reformation that caused Francesco and his courtiers not to make such themes too evident. In the grotto analyzed here, the function of the automata of the Samaritan is to shift attention to the element of water, while the automata of the Forge of Vulcan promoted the representation of the element of Fire. This was the meaning of the myth according to its ancient origins.

The meaning of the myth of the Forge of Vulcan, however, had been significantly enriched during the early modern time. The capacity to artificially induce the element of fire in order to provoke transformations of other elements was more and more associated with technical abilities in the framework of metallurgy and, especially in Florence starting from the late 1570s, with the ability to construct fire weapons. Generally speaking, the iconographical power of the myth of the Forge of Vulcan was able to encompass all the specific early modern activities related to the Art of War, which had been revolutionized during the second half of the sixteenth century.

However, the close proximity of the Forge of Vulcan to the activities related to the fortress was not only realized in the grotto of the Samaritan. In the Duchy of Tuscany of Francesco I, there was a close relation between the scientific and artistic enterprises scattered all over the territory. Apart from the proximity of the program of the Studiolo to the realization of Pratolino, the garden can be understood also by analyzing the realizations achieved in another Florentine building site, the Uffizi.

The construction of the Uffizi started already under Cosimo I in 1560 and was finished by the time of the reign of Francesco I. However, it was Francesco who ordered all the ceilings of the gigantic building to be painted and who created the famous Tribuna, finished in 1585. At the centre of the Tribuna, which was also conceived and built under the supervision of Bernardo Buontalenti, was an octagonal table, just as in the grotto of the Samaritan. The rooms that led to the Tribuna, according to the route conceived by Francesco, were the

[75] Francesco's adhesion to the alchemic culture is evidently shown by the famous painting of Stradanus of the alchemist's workshop. This was painted in Florence at the request of the same Francesco and represents the Duke himself as the master of the workshop.

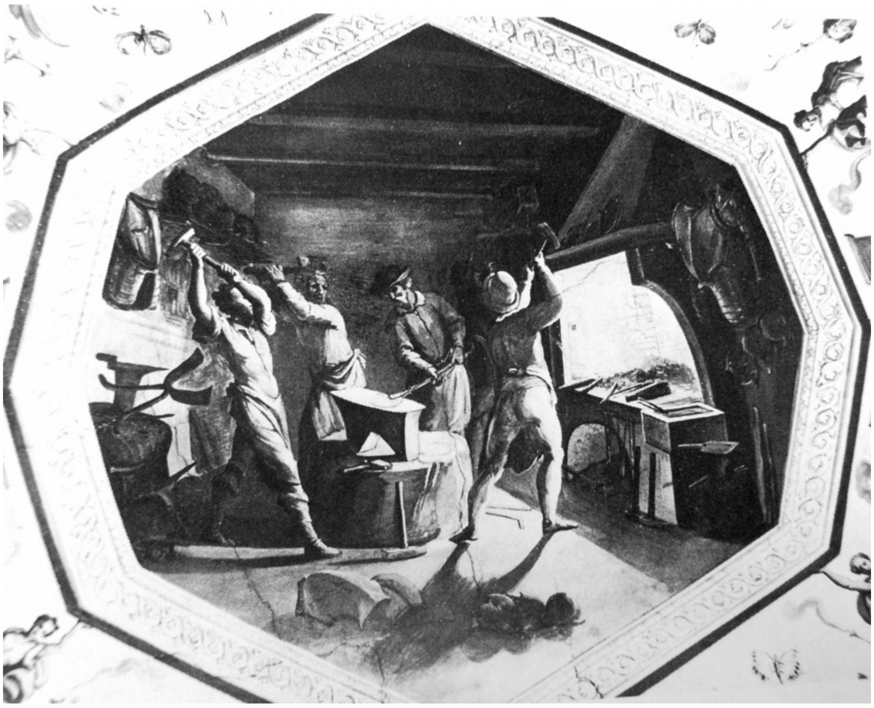

Figure 5 *Forge of Vulcan. Ludovico Buti, 1579–1581, Fresco, Palazzo degli Uffizi, Florence, Room 23. Su concessione del Ministero dei beni e della attività culturali e del turismo. Reproduced with permission of the copy right owner.*

socalled rooms of the armory, the ceilings of which were painted by Ludovico Buti between 1579 and 1581. The first of the armory rooms, the one nowadays identified as room twentythree, shows a series of frescos that clearly reproduce some of the subjects of the grotto of the Samaritan as well. A forge for small weapons, a workshop of cannonmakers, a workshop for the production of gunpowder, and a workshop for the production (and conception) of military fortresses, are all depicted around the central fresco representing the Forge of Vulcan (Fig. 5).

When details of this fresco, such as the position of the fire and the position and gesture of the artisans, are compared with those of another illustration, namely with a drawing preserved at the Gabinetto dei Disegni e Stampe of the Uffizi (Fig. 6), it turns out that both the fresco and the drawing clearly show the same subject, in exactly the same manner.

The drawing of the Gabinetto Disegni e Stampe represents a complex automata system powered by water. The drawing is attributed to the engineer Giulio Parigi, who obtained the position of First architect and engineer of the

Figure 6 *Giulio Parigi's drawing of an automata representing the Forge of Vulcan. End of thesixteenth century. Pen and watercolors. 37,3×26,7cm. Gabinetto di Disegni e Stampe degli Uffizi, Florence, 588277. Su concessione del Ministero dei beni e della attività culturali e del turismo. Reproduced with permission of the copy right owner.*

This text was published on page 160 of the article "Ancient pneumatics transformed during the early modern period.".

Grand Duke just after the death of Buontalenti in 1608. Giulio Parigi was the son of another famous Tuscan engineer, Alfonso Parigi, relative of and partly educated by the famous engineer Bartolomeo Ammannati, and finally a pupil of the same Buontalenti. Giulio Parigi was born in 1571 and was certainly a pupil of Buontalenti during the 1580s.[76]

In 1969, the art historian Annamaria Petrioli Tofani dated the drawing of the pneumatic automata back to 1608, because in the same year the recital of the comedy *Il giudizio di Paride* took place on the occasion of the wedding of Cosimo dei Medici and Maria Maddalena of Austria, precisely on October 25. For this recital, Giulio Parigi was charged with the preparation of the scenog-raphy of some of the intermezzi. The intermezzo number five finally was the one where Vulcan forges the weapons to conquer Sparta. Giulio Parigi left a drawing of this scenography that shows how he intended to use some sceno-graphic machinery placed under the stage of the theater, but there is no indica-tion that the Vulcan and its forge was a complex of water-powered automata. Considering, moreover, that the recital took place in the theater conceived by Buontalenti and that therefore the Forge of Vulcan would have had to be of sig-nificant dimensions, it turns out to be very improbable that such a large device was used in a theater and powered by water for only one aspect of one of the eight intermezzi of a lengthy recital. Observing the drawing of the automata, moreover, the complex machinery is clearly inserted in the context of grottos, which reminds one of the garden of Pratolino.

The movements of the artisans of the automata, described in the text of Sgrilli above, clearly coincide with the movements the automata are able to accomplish according to the drawing of Parigi. The hypothesis that Parigi's drawing represents the automata of the Forge of Vulcan built in Pratolino is further supported by a second drawing of Giovanni Guerra concerned with the Grotto of the Samaritan (Fig. 7). The second drawing shows machinery related to the list of small automatic artisanal workshops described above. Although this machinery mostly refers to other practical activities and therefore does not represent a source that demonstrates the presence of a certain precise

[76] For extensive studies on the tradition of Tuscan engineers, with particular attention on the work of Giulio Parigi, see Daniela Lamberini, "I Parigi, una famiglia di artisti pratesi alla corte medicea," in *Prato e i Medici nel '500. Società e cultura artistica* (Roma: De Luca Editore, 1980), pp. 135–157, Daniela Lamberini, "Boboli e l'ingegneria idraulica alla scuola dei Parigi," in *Boboli 90* (Firenze: EDIFIR, 1990), pp. 467–479, Daniela Lamberini, "Cultura ingegneristica nel Granducato di Toscana ai tempi dell'Aleotti," in *Giambattista Aleotti e gli ingegneri del Rinascimento*, edited by Alessandra Fiocca (Firenze: Olschki, 1998), pp. 293–308.

Figure 7 *Machines of the Grotto of the Samaritan. Giovanni Guerra, Architektur, Graphische Sammlung, Albertina, Vienna, 1598, no. 37221v (www.albertina.de).*

realization of the Forge of Vulcan, it does testify however to the presence of such machinery before 1598.

There is therefore good circumstantial evidence that the automata of the Forge of Vulcan was built during the 1580s, that is, before the death of Fran-

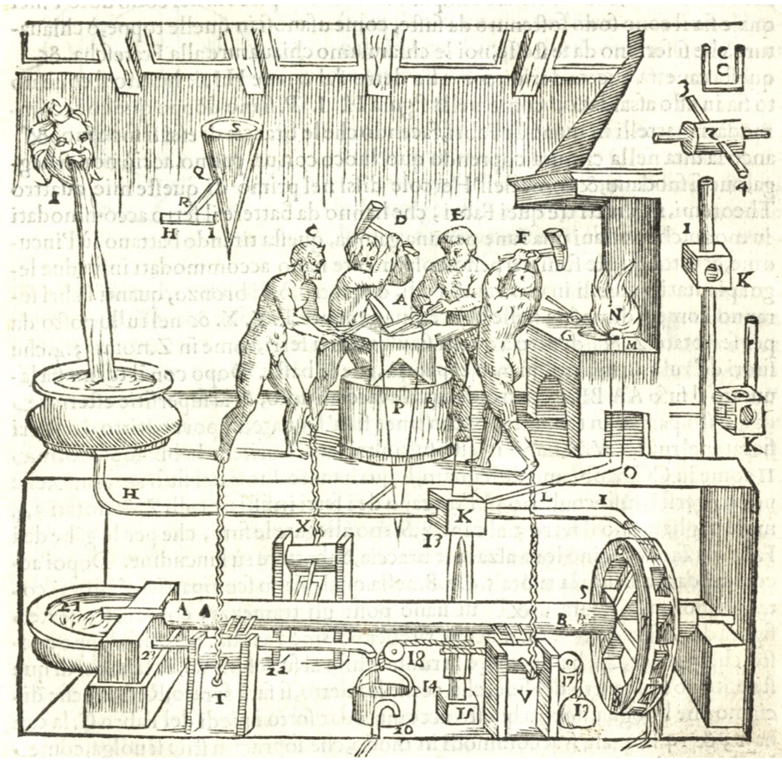

Figure 8 *Giovan Battista Aleotti's pneumatic automata of the Forge. From Hero of Alexandria and Aleotti, Gli artifitiosi et curiosi moti spiritali di Herrone, p. 93. Courtesy of the Library of the Max Planck Institute for the History of Science.*

cesco I on October 19, 1587. As Giulio Parigi was undertaking his apprenticeship with Buontalenti during this period, and because Parigi's interest for pneu-matic devices and for the automata of Pratolino was particularly intense at that time,[77] it can be assumed that Parigi's drawing was realized in the 1580s as well.

Having established that Parigi's drawing represents the automata of the Forge of Vulcan built in the Grotto of the Samaritan at Pratolino during the 1580s, the same drawing can be compared to another illustration published earlier in 1589. This drawing represents one of the so-called new theorems

[77] Ibid (cit. note 76).

that Giambattista Aleotti added to his edition of the *Pneumatics* of Hero of Alexandria published in 1589 (Fig. 8).[78]

It is absolutely evident that the two drawings are almost identical, though some differences can indeed be observed. First, there are scenographic differences, which, however, do not imply any difference from the mechanical point of view. On the left side, Parigi's drawing shows a water wheel while Aleotti's drawing depicts a simple water basin. Parigi's water wheel, however, does not seem to be connected to any further mechanical device. From the point of view of the mechanics of the automata, only the water that falls into the hidden mechanisms below is of importance, as it powers the entire complex. This water is conveyed into a pipe, which jets water onto the right side of the lower section and powers another water wheel. By comparing the two drawings, it becomes clear that Aleotti's technical suggestion would work in exactly the same way. On the right side of Parigi's automata, moreover, one can see parts of a mill in agreement with Sgrilli's description quoted above. This mill is not present in Aleotti's drawing as his purpose was not to recreate the whole grotto with his complete iconographical and iconological program. Concerning the mill, moreover, this seems to be a typical mezzo-conica mechanical device on which Buontalenti seems to have been working during the same period, as an hitherto unknown drawing preserved at the Gabinetto dei Disegni e Stampe of the Uffizi (MFF_2305A–V) clearly shows. The movements that the figures of the artisans are able to accomplish are also exactly the same. For instance, artisan E in Aleotti's drawing is the one who turns to the fire with the pliers, takes the metal to be hammered, and turns back displacing the object on the anvil. Again, this demonstrates complete agreement between Aleotti's and Parigi's drawings.

The drawings of the figures show differences concerning the positioning of some of the artisans, depicted in one drawing with the hammer on the anvil and in another with the hammer in the air. Aleotti chose to depict a moment of the moving automata that in fact closely resembles the fresco of Ludovico Buti at the Uffizi, from which this argument evolved.

Finally, there is one significant difference between the two automata complexes. Aleotti's drawing shows a device whose function is to jet water out from the anvil, each time a hammer hits the metal. This is the cone that can be seen under the anvil and that Aleotti depicted also in the upper part of the drawings toward the lion's head – a cone with a lever – in order to explain how it works.

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[78] Hero of Alexandria and Aleotti, *Gli artifitiosi et curiosi moti spiritali di Herrone* (cit. note 31), pp. 93–95.

Considering that this automata was built in Pratolino during the 1580s, one can conclude that Aleotti's new device originated in and was inspired by the general attention regarding the myth of Vulcan spread by the Florentine court, the fresco of the Uffizi, and finally, by the fame of the garden of Pratolino, especially the sophisticated water-powered tricks built in its grottos. Given the architects' and engineers' habit at that time to circulate drawings, and especially to use such drawings as a source without the need to clarify which sources they actually used, it is possible to conceive that Aleotti became aware of such an automata from a drawing like Parigi's, or even a copy of it. The evident similarity between the two drawings clearly shows that they are somehow associated with each other. It is known that Aleotti knew about Pratolino and that at the end of the 1580s, he also requested the Grand Duke to accept his services as an engineer. It is also known that Aleotti visited Pratolino, though only in 1591, two years after the publication of his commented translation of Hero's Pneumatics. Thus, it was not during this visit that he became aware of this machine for the first time.

Considering the origin of the subject, which is the fresco Buti painted between 1579 and 1581, and considering as well how Francesco I was obsessed with this myth – he also commissioned the artist Vincenzo de' Rossi in the 1570s to create a statue representing Vulcan for his Studiolo – it seems clear that the construction of Pratolino's automata must have taken place, or at least been commissioned, while Francesco was alive, that is, before 1587. Therefore one may conclude that Aleotti's drawing was inspired by the construction of Pra-tolino.

Aleotti decided to publish the description of the water-powered automata complex of the Forge in his edition of Hero's *Pneumatics*. The explanation for Aleotti's decision is that Pratolino was indeed conceived as a realization of Hero's program to such an extent that even the new machines built in Pratolino were somehow associated with the classical ones, whose descriptions had been passed down from the ancient times.

Not only was Buontalenti considered to be a modern Hero of Alexandria, but also the garden he designed and built was considered to be a modern translation of Hero's *Pneumatics*. This created additional value to the text of Hero. The engineers tested the ancient technology in it and decided to follow the ancient path and to codify their new technological artifacts as Heronian.

7 The transformation of the Science of Pneumatics

After having established the line that connects both of the main Italian editions of Hero's *Pneumatics* to the garden of Pratolino, it turns out to be particularly relevant to return to the theoretical debate concerning the existence of interstitial vacua, the constitution of the elements and matter and, in particular, how this debate was revitalized in the new early modern editions of the work.

In the works of Oreste Vannocci Biringuccio and Giovanni Battista Aleotti in particular, Hero's theoretical explanation for the functioning of his pneumatic devices is translated, commented, and, in spite of the successful technical tests, also criticized.[79]

To introduce the reader to Hero's work, Biringuccio, at the beginning of his 1582 translation, undertook a defense of the Aristotelian doctrine, in particular, concerning the question of the vacuum because "from his proemium [Hero's] it is clear that he wrote during a time when the Peripatetic doctrine did not yet have authority."[80] Biringuccio took it for granted that Heronian contraction and expansion are scientific concepts used to explain the same phenomena that the Aristotelian concepts of condensation and rarefaction also explain. Then he continued:

[…] rarefaction and condensation, as established by Aristotle, really make those effects which were […] ascribed to the vacuum scattered among the atoms, or particles of all the things, and it is clear that rarefaction and condensation do not take place because the parts of the bodies receive more or less vacuum among themselves […], but because, since the rarefied bodies are those which have in themselves less matter in a form which needs great dimensions, and since on the contrary the dense bodies are those which retain a lot of matter in a form which requires small dimensions, the rarefaction of a certain body takes place because the matter, when it prepares itself to change into another form, for which

[79] An extensive study on the early modern reception of the theoretical approach of Hero of Alexandria during the early modern period can be found in Matteo Valleriani, "From Con-densation to Compression: How Renaissance Italian Engineers Approached Hero's Pneu-matics," in *Übersetzung und Transformation*, edited by Hartmut Böhme, Christof Rapp, and Wolfgang Rösler, *Transformationen der Antike* (Berlin: DeGruyter, 2007), pp. 333–354.

[80] Hero of Alexandria and Vannocci Biringuccio, "Libro degli artifizii spiritali over di fiato d'Herone Alessandrino" (cit. note 25), fol. 2r. The original text reads: "[…] dal proemio suo si conosce che scrisse nel tempo che la dottrina peripatetica non haveva ancor autorità […]."

greater dimensions and greater quantities are needed, it is obliged to spread out so that it is suitable to that [form], although to the matter, as matter, no determined figure or dimension can be ascribed, because, realizing the accidents, is proper of the form […].[81]

The parallelism between, on the one side, condensation and rarefaction and, on the other side, contraction and expansion, obliged Biringuccio to take into consideration the case of a body, for instance, water, which changes its form to vapor [air]. Thus, after explaining this process in detail, he returns to the general terms taking into account the real problem given by Heronian vases, where no change of form takes place:

[…] rarefaction and condensation suffice […] to explain all the experiments adduced by Hero […] about cupping-glasses, of the sucked vase, and of the inflated sphere, and of whichever other similar vases, which can be adduced and that, either naturally or artificially, become attracttive and expulsive, although such effects happen because of rarefaction or *excessive condensation*, which is also hated by nature, and tolerated only because of temporary short violence.[82]

[81] Ibid. (cit. note 25), fol. 2v–3r. The original text reads: "la rarefattioni e' condensationi stabilita da Aristotile fa veramente gli effetti che eron da quelli fuor di ragione attribuiti al vacuo sparso tra gli atomi, o, particelle di tutte le cose, et è cosa chiara che la rarefazzione el condensamento, non si fanno perche le parti de corpi ricevino piu, o, men voto fra' di loro com' essi credevano, ma perche essendo corpi rari quelli che hanno in se poca materia sotto forma bisognosa di gran dimensioni e' per il contrario essendo corpi densi espressi quelli che molta materia ritengano sotto forma a chi di piu piccole dimensioni fa di bisogno, il rarefarsi d' alcun corpo succede, perche la materia nel disporsi per passar in altra forma alla qual si ricerca piu ampie dimensioni, et maggior quantità vien per forza a distendersi per adattarsi a' quella peroche alla materia in quanto materia non conviene alcuna figura, o dimensione determinata per esser proprio della forma determinarsi gli accidenti." This message might refer to the doctrine of Cardano (see footnote no. 19), however, no reference supports this inference.

[82] Ibid. (cit. note 25), fol. 3v. Author's italics. The original text reads: "la rarefattione el condensamento, come anco basta a' salvar tutte l'esperienze addotte da Herone e' dagli altri delle ventose, del vaso succhiato, e' della sfera gonfia e' quant' altre simili se ne potessen addurre di vasi che per natura, o per arte diventino attrattivi o espulsivi, pero che tali effetti avvengano per la rarefattione o, condensamento soverchio che è anch' esso odiato dalla natura è sopportato solo per violenza breve tempo."

This text was published on page 167 of the article "Ancient pneumatics transformed during the early modern period.".

Heronian vases definitely challenged the Aristotelian doctrine, as Biringuccio was aware. He attempted to retain the general structure of the Aristotelian doctrine by adducing the processes of condensation and rarefaction to explain those of contraction and expansion as well. Following Hero, he focused in particular on the process of contraction and described it as being caused by a sort of special condensation, also abhorred by nature, but, if short enough, one that can take place due to a violent action. The process *of excessive condensation* is supposed to explain how a body, for instance air, could condense (contract) without changing its form, but in a way that allows it to return to its natural state.

This step is clearly relevant because, first, it shows that Biringuccio recognized that the Aristotelian doctrine was not adequate to describe the pneumatic phenomena relevant for Hero's approach. Second, Biringuccio admitted that processes that went against nature could be realized, although he mostly remained within the Aristotelian frame. He adapted it only slightly to meet the new challenges that realizations such as those of Buontalenti in Pratolino were about to popularize. Finally, Biringuccio refused to take into account the case in which a heat source is applied to the pneumatic device.

Only seven years later, in 1589, Giovan Battista Aleotti also added a commentary to the theoretical preamble of Hero of Alexandria in his edition.[83] The title of this chapter is "Aleotti's addition concerning the impossibility of the existence of any vacuum, and a claim that the element of Air cannot be compressed." Despite this title, the content of the chapter is much more tolerant toward Hero's doctrine. He postulated both the possibility of creating a large-sized vacuum, not inside the elements but outside the bodies, and the possibility that elements can be compressed, thereby coming extraordinar-ily close to the modern concept of fluid mechanics which originates in the research of Robert Boyle.[84] Since the text is relatively short, it is worth reading in its entirety:

According to what Hero said above, one could add that if one takes a stick [a ramrod (*calcatoio*)] as an arquebus, at whose end there is a well-made rabble and we insert it into the barrel of the arquebus, perfectly drilled along a straight line using the greatest of skill and, if the opening toward

[83] Hero of Alexandria and Aleotti, *Gli artifitiosi et curiosi moti spiritali di Herrone* (cit. note 31), p. 8.
[84] See also, A.G. Keller, "Pneumatics, Automata and the Vacuum in the Work of Giambattista Aleotti," The British Journal for the History of Science, 1967, 3:12, pp. 338–347.

the firing mechanism is closed and we pull it out [the stick] almost completely, this will happen only with a certain effort as it is opposed by the vacuum that is created at the bottom [of the barrel] as the air cannot enter. If then, when the stick is almost out of the barrel, we let it go, the vacuum will pull back the stick violently to fill [the barrel] again, as that vacuum can only exist because of a violent action on nature. That the element of air can only remain in the quality [status] according to its nature and in the way God Almighty created, it can be proved also in another way. Once the opening between the barrel and the firing mechanism is closed and we insert the above-mentioned stick, we will experience that we can do this only by means of a certain effort, as the air is a body and this will crowd together [*ammassarsi*], and if once pushed down as far as possible, we let it go, the air is subjected to violence since it cannot remain packed [*constipata*], it will break out, and with fury push out the stick and so return (once the violence stops) to its natural state. Hence it is clear that if we insert a ball when the opening between the firing mechanism and barrel is closed, as the packed air wants to go back to its natural status, it pushes it out violently. This therefore shows that the vacuum cannot exist and that this element [air] can only stay in that natural status, as the Creator created it.

One proves moreover that no vacuum can exist also by means of those glass vases used by women to decrease and partially empty their breasts of the milk they receive so abundantly two or three days after a birth, because if the children born do not empty them, they would cause themselves hardness and very severe pains if they did not decrease their breasts. These [vases], as it is known, are constituted by a body with a hole large enough so that, when they lean the vase on the breast, the nipple comfortably enters it. On the other side, they [the vases] have a neck long enough to be taken into the mouth and, once the inside Air is sucked out, the milk follows immediately out of the breast. And it works [it can be proved] also by means of those cruets that they normally use to achieve the same goal.

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 vacuums [pores], pushes the air out from it and fills the body of the cruet with a very thin vapor, and when 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 vacuums [pores] 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 transformed into aerial substance, and since through these small pores, which are very thin, the air cannot enter, and since the vacuum cannot exist [persist], that body, which cannot stay empty, immediately pulls milk from the breast, and by emptying it [the breast], it [the cruet] fills itself, and when it is completely full, it ceases pulling, in the same way as, if it is open at a certain position, one lets the air enter into it.

Similarly the fires that are set at the mouths of the furnaces (within which stones, lime mortar, and earth vases are fired) are pulled into those furnaces by the vacuum. This happens because the vapor of the fire, once it has pushed out the air which is inside, vanishes and evaporates upwards and, as the fire is at the mouth of the furnace, it blocks it [the mouth] and the air cannot enter. When the vapor has vanished, as the vacuum cannot exist [persist], the fire fills the empty body that would be created in the furnace because, when the vapor exits, the opening for the air is closed and, as the vacuum cannot exist [persist], the fire substitutes the vapor.

From these things the high excellence becomes clear, by means of which Hero has proved that the vacuum cannot exist if not by means of violent action and outside natural terms.

Aleotti's theoretical notes concerning Hero's preamble describe five experiences, all of them pertaining to real life, though not necessarily common. The first two experiences he describes could only have been known to those who were familiar with the arquebus. Two experiences were related to medicine and, in particular, to devices that extract milk from women's breasts after giving birth; the last experience involves the functioning of furnaces. In the frame of the sixteenth century, the experiences Aleotti refers to are elaborated arrangements, which had already proven to be replicable and could not be contested in reference to their execution.[85]

The overall goal of Aleotti's chapter is to show that void can be created artificially and violently. The medieval principle that nature abhors vacuum,

[85] For an analysis of Giovan Battista Aleotti's method as anticipation of the emergence of modern empiricism, see Matteo Valleriani, "Sixteenth-Century Hydraulic Engineers and the Emergence of Empiricism," in *Conflicting Values of Inquiry: Ideologies of Epistemology in Early Modern Europe*, edited by Tamas Demeter, Kathryn Murphy, and Claus Zittel (Leiden: Brill, in press).

therefore, is interpreted in its weak variant, namely, that nature alone cannot create vacuum, but that it can nevertheless be created artificially.

The terms with which the engineers discussed Hero's theories, only seven years after the first Italian translation had appeared, changed dramatically. In the title of his additional chapter, Aleotti already distinguished between the phenomena described by the Aristotelian principles of condensation and rarefaction, and those phenomena described by Hero to explain the functioning of his pneumatic devices. Aleotti abandoned the Aristotelian frame and accepted the Heronian one when he declared that air could be "compressed," though only for a short time. In this sense he also retrieved the temporal characteristic of the effects of the process of "excessive condensation," as postulated by Biringuccio.

If, according to Aleotti, air can be compressed, the concept of air compres-sion or even air compressibility is nevertheless far from being defined. In fact, air can also "crowd together" (*ammassarsi*) or "be packed" (*constiparsi*). However, a relevant difference between Aleotti's ideas and Hero's doctrine itself persists. Although Aleotti admitted that air could be compressed and although he believed that an external vacuum could exist, he did not seem to accept the fact that air is constituted of particles and interstitial vacua. Aleotti's packed air and Hero's contracted air are two bodies with completely different internal structures.

Aleotti refused the Aristotelian principles of condensation and rarefaction, the Aristotelian impossibility of the vacuum, and Hero's interstitial vacua, and retained only the possibility to create an external vacuum by means of a violent action. Apart from the unresolved question of how air is then constituted, this conceptual system, however, seems sufficient to explain the functioning of many of Hero's pneumatic devices, but indeed not all of them. In particular, Aleotti could not leave the question unanswered of how a device operated by a heat source works. For this purpose Aleotti involved a conception of heat in his argument, which differs significantly from that of Hero. As quoted, he explained his theory by means of an example, that is, directly describing the functioning of a pneumatic instrument that is operated by a heat source to suck milk from a woman's breast.

While Hero's heat corrupts and makes the particles of the air thinner so that they escape from the vase, in Aleotti's case, the heat is a thin vapor that penetrates the vase and pushes the air away.

From a technical point of view, the superiority of Hero's explanation is evident: whereas Hero's approach can explain the behavior of the air independently from the characteristics of its container and in particular independently from whether it is open or closed, it remains completely unclear what happens, if, according to Aleotti's idea, a closed container with air in it is heated. Either the igneous vapor cannot penetrate it because the air does not find a way to escape and the container remains cold, or the igneous vapor is able to operate a certain pressure so as to "pack" the air. However, connections between pressure and temperature were still far from being discovered. Despite this fact, Aleotti nevertheless paved the way and was followed by scientists who researched the nature of heat in connection to pneumatic phenomena as, for instance, Galileo did for many years until he accomplished his "atomistic" conception of heat published in the *Saggiatore*.[86]

In conclusion, the first Italian translations of Hero's *Pneumatics* are not only closely linked to the technological enterprises of the time and, in particular, to the amazing location of Pratolino, but they are also the path and the method for codifying a series of new theoretical ideas that, seen in their entirety, testify to a profound theoretical transformation based on the ancient source.

8 Transformation and Practical Knowledge

Throughout this work it has been shown how Pratolino was built according to the Heronian program, which became available after the *editio princeps* of Commandino in 1575 and, above all, after Biringuccio compiled the first commented Italian translation at the request of Buontalenti in 1582. In practice, the garden of Pratolino, which immediately became renowned as the most advanced center of applied hydraulics and pneumatics in Europe, represented a sort of workbench on which the suggestions of Hero of Alexandria were tested. The successful conclusions of these tests on Hero and his work caused him to become the ancient authority of the early modern engineers. They commented on his work in order to enter the scientific debate of the last phase of the sixteenth century, in a similar way to the commentators of, for instance, Aristotle's *Mechanical Questions*.[87]

The engineers used Hero's work on a number of levels. They used the struc-ture of his work, for instance, which was constituted of a first section dedicated to the theoretical principles and a second one in which the technical descrip-tions of all the devices are given. Both Oreste Vannocci Biringuccio in 1582 and Giovambattista Aleotti in 1589 added a theoretical chapter to Hero's *Proemium*, dedicated to the theoretical principles of pneumatics, and technical descrip-

[86] Matteo Valleriani, *Galileo Engineer* (cit. note 3), Chap. 5.
[87] Matteo Valleriani, "The Transformation of Aristotle's 'Mechanical Questions'" (cit. note 6).

tions of new devices at the end of the book, following Hero's descriptions of the hydraulic and Aeolian organs. The technical descriptions of the devices in Hero's work follow a precise scheme constituted of a title, short statement, and demonstration, very similar to the structure of the Euclidean propositions of the *Elements*. When the engineers began to add technical descriptions for new devices, they used exactly the same narrative structure.

What is more relevant, finally, is that the engineers began to codify their theoretical principles in order to find a solution to the theoretical problems that were first singled out and determined by Hero and not by themselves. According to Hero, it was the problem of the constitution and nature of the elements of air, water, and fire that had to be solved in order to be able to explain properly the functioning of pneumatic devices. And it was the search for a solution to this same problem that led the engineers to codify their conceptions in theoretical chapters of their editions.

Modern pneumatics was therefore clearly generated by engineers who connected their works to ancient science and technology and transformed it into the new context constituted by the results achieved during the early modern period. What this research suggests is that such a process of transformation, which is also a process of appropriation of ancient science, could only take place after two historical conditions had been fulfilled. The first condition was that the ancient texts had to become widely available. The second condition was that the ancient technology had to be proven to be valid, that is, the devices suggested by Hero had to work. This research shows that the second condition was realized by the construction of the garden of Pratolino.

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