PHD ABSTRACT

The aim of this thesis has been to argue, on the basis of primary sources, that Huygens was a pioneer in the field of mechanical engineering. He fits the definition of a mechanical engineer as somebody who develops a novel invention either empirically or theoretically, using known mechanical theories. In the same way, a new invention may come about through transforming an existing machine or instrument thus revolutionizing any future versions of it. Huygens did both he applied a pendulum to existing clocks and transformed the making of precision instruments from that moment onwards.

The first chapter of the thesis presents Huygens' works on pendulum clocks and marine clocks. The second chapter is dedicated to Huygens' research and designs of the air pump and linking with the third chapter on matter theory. The fourth chapter focuses on Huygens' designs of various instruments (the telescope, the microscope, the level, the planetarium and others). The final chapter depicts Huygens in the societies in which he lived.

Huygens was a pioneer of mechanical engineering because he presented a complete work on mechanics to explain instruments, 'automata', by mathematical axioms and laws. Furthermore, he developed a methodology for improving instruments and machines based on searching for the best materials to obtain the best working models. The Horologium Oscillatorium of 1673, was a textbook, which inspired others to continue a tradition of mechanics for the mechanical engineer. With geometrical ratios he was able to show the applicability of technology in everyday life. Therefore, Huygens took the foundations of mechanics further than his contemporaries did. The geometry he used was the basis, which could simplify and give a quantitative measure of nature and of any man-made instruments alike.

CONTENTS

INTRODUCTION

Much has been written about Christiaan Huygens, dealing either with his better-known treatises or with his life in general[1]. However, a new and fuller appraisal of his work is needed and this thesis tries to do that by using neglected source material. I believe that he was a natural scientist with an optimistic outlook and a scholar in more fields than he has been given credit for. However, I will also present him as a professional inventor and a pioneer in what later became mechanical engineering.

Christiaan was born in The Hague on April 14 1629 to a diplomatic family and died in the same city on July 5 1695. His father Constantijn was a well-known diplomat and poet, and one of his brothers, Constantijn, followed his father's career. The father created a carefully worked out liberal education in which, from an early age, languages played a significant role. Constantijn made studies attractive for his children. He engaged a series of private tutors with whom he devised a very good curriculum. Education was an enjoyable task in the Huygens' household and Christiaan continued this attitude toward learning all his life. It was an intense education, which included practical issues such as lens grinding, or the study of Descartes' more modern ideas. These Christiaan soon understood under the tutelage of F. Van Schooten at Leyden University[2], in 1641, where he and his brother Constantijn were studying. Van Schooten included Cartesianism in his curriculum at a time when the French philosopher was considered too advanced and his philosophy became increasingly polemical in Academic circles. Later, Huygens was at the Atheneum in Breda, where he read law and studied mathematics privately with Pell[3]. From a very early age, he showed great mathematical skills, and his mathematical style followed Archimedes' geometry[4] and adapted it to most of his works.

The contacts of his father at the French court included learned men of the time, who later were to be an important asset to the young Christiaan. Not that he needed much help, since he soon emerged as a prodigious student, but they helped to accelerate communications and correspondence between natural scientists from both countries and later also from England. Huygens was very popular and highly respected by his counterparts throughout his lifetime because of his work as a scholar and his creativity. The wide range of fields researched on was also influenced by his first trip of 1661 to France and England. During that time he encountered scientific circles which discussed varied issues, different from the debates taking place in the Academic world. He was also invited to the 'salons', where he was admired for his learning; no title was needed to belong to the meetings organized by 'les cultes'. This trip started to shape Huygens' objectives and he returned to The Hague with a good impression and with an awareness of the importance and need for an empirical science. It was different from his geometry and mechanics, and for the studies in astronomy for which he was already recognized as a professional. Initially Huygens was invited to the Court of Louis XIV as an inventor who had understood the importance of empirical demonstrations at the meetings that he had attended at the scientific societies in France and England. Huygens appreciated the possibilities that new ideas offered for scientific research, and the air pump, which he designed and used in experiments, is just an example of this. He set out to make his own contribution in as many fields of knowledge as he could, in particular, in mechanics. He described his designs and developed a geometrical theory to account for the way in which instruments worked.

The 'new science' started to emerge outside the universities. An important difference between the academic and the scientific organizations was not only the rapid exchange of ideas and solutions to problems through the correspondence of the members of the scientific academies, but also the use of the vernacular which allowed for a faster popularization of the new ideas. Therefore, three traditions developed and converged, more differentiated in those countries where there were scientific organizations: the Royal Society (England); the Royal Academy (France); the Accademia del Cimento (Italy); Huygens and others in The Netherlands, where no organization for science was created in the seventeenth century. At universities there was an Academic tradition, whose curriculum was based on the traditional philosophical discourse. Another tradition was that of the 'new science' with a mathematical and empirical basis. The third tradition developed from laboratory assistants and craftsmen, who also contributed to a new concept of technology and the use of designs from scholars, such as Huygens, in instrument-making. In the latter, it is important to differentiate between the instruments used for experimentation and often made by experimenters themselves, and those made by craftsmen for the open market.

The aim of this thesis is to argue, on the basis of primary sources, that Huygens was a pioneer in a new field in engineering, later known as mechanical engineering. He fits the definition of a mechanical engineer as somebody who develops a novel invention either empirically or theoretically and the mechanical theories to explain it. In the same way, a new invention may come about through transforming an existing machine or instrument thus revolutionizing any future versions of it. Huygens did both; he applied a pendulum to existing clocks and transformed the making of precision instruments from that moment onwards. He also created novel machines as will be seen throughout this thesis. I have found that, although good work has been carried out on Huygens' manuscripts, unfortunately this has been done in a very partial manner. I intend to study Huygens as a professional who influenced and helped to shape modern science. My thesis is an attempt at giving Huygens the place he deserves in the history of science. This has often been shadowed by the biased interest paid to other scientists of the past. Although there are abundant secondary sources, this thesis is not a historiographical study. I am, however, indebted to many historians of science whose work I have drawn on to support my argument, or whose views, though different from mine, have been stimulating.

The reader should have a clear idea of the difference between an inventor and a mechanical engineer before reading this thesis. Mechanical engineers do not necessarily invent but improve existing devices. For instance, a car does not get invented continuously, instead engineers find better ways to reduce fuel consumption, better materials etc. And the theory they only need to study has been developed by the work of pioneers such as Huygens, Newton and after the XVII century, physicists who keep improving the existing theories. The methodology also has to be understood as different from other argumentative methods. The "facts" are taken as references from manuscripts to prove the hypothesis, hence the regular use of specific terminology: mechanical engineer, mechanical engineering.

This thesis tries to present a revision of Huygens' work and the pivotal role he played in the scientific community of the seventeenth century. He was known even to people who were not specialists and, in particular, to the scientific community of the time. His accomplishments in dynamics: the laws of impact; conservation of momentum; the isochrony of the cycloid; universal measure (g); centrifugal force and work related to the clock and the air pump, have been fully documented (Bell, Bos, Brusa, Gabbey, Herivel, Leopold, Mahoney, Slenders, Stroup, Westfall, Yoder). Very few historians have researched in other areas. There are some exceptions. Shapin and Schaffer recently produced a study on Huygens' experiments with the air pump, and more recently, Fournier has paid attention to Huygens' microscopes. Huygens was also admired for his work in different fields such as: optics, lens grinding, astronomy, microscopy and natural philosophy. All this made him not only an engineer, but also a natural scientist. It is as important to recognize his pioneering work (the pendulum clock, or the corpuscular-wave theory of the propagation of light) as to understand the limitations he encountered when he had to find new theories to describe new phenomena (the air pump). However, these were problems all his contemporaries had to face. It was the beginning of other fields of science, and 'theoretical physics' had hardly developed.

Chapter 1 presents Huygens' most advanced studies, which made him the forerunner of mechanical engineering: clocks, in particular, pendulum clocks. He referred to clocks as machines or automata[5]. Special attention has been given to his different designs, dating from 1657 to 1673, and to the marine clocks of the 1680s and 1690s. Similarly, chapter 4 focuses on Huygens' designs of various instruments: those used to grind lenses, the optical instruments (the telescope, the microscope and the level), the planetarium and others.

Chapter 2 is dedicated to Huygens' air pump. Unfortunately, he did not think this work good enough to deserve a full treatise for publication. Most of the primary sources on this subject are found in the correspondence. The air pump had been initially built to obtain a vacuum and developed into an instrument with which it was possible to find more about the physical qualities of natural elements. Although a difficult task, Huygens tried to develop his own theory of matter (chapter 3) and by doing so, he entered a very different field of knowledge than that of the pendulum clock.

Chapter 3 assesses Huygens' theory of matter. It begins with the theories on rectilinear and circular motion and the treatises he wrote on them. The concept of motion was at the core of Huygens' mechanics and fundamental in the descriptions of the properties of material bodies. He could not find a geometrical theory for the air pump. This encouraged him to develop a theory based on 'theoretical physics' with some simple mathematical notation. Later in life, influenced by the new theories on the infinity of worlds, Huygens wrote his own cosmology. He argued that since matter surrounded the planets in the solar system that there must be other universes with planets and inhabitants similar to ours. This he had concluded after a long career of observations with his telescope.

The final chapter depicts Huygens in the societies in which he lived. Here there are several important questions: Did Huygens develop all his ideas driven by the scientific society of the time, or by the interests of a very wealthy Court? Was his own scientific interest and intellectual curiosity, which made him pursue so very different fields of knowledge? How much freedom did he have to be able to develop instruments other than those commissioned by Louis XIV? How influential was he amongst his contemporaries and within the Court? Was he still admired during the Dutch war with France when he remained at the French court? Was his work lost in the mist of time, due to lack of attention on the part of historians of science? Has this inattention been due to an exaggerated emphasis on the role played by the hero-scientist and, therefore, shrouding very important scholars who do not match this concept?

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[1] (Dr.D.J.Struik, Het Land van Steven en Huygens, Nijmegen, SUN, 1979, pp.97-109; H.J.M.Bos edit. Studies on Christiaan Huygens, Swets & Zeitlinger B.V.1980, p.7-26).

[2] (Leyden university was the first one to be opened in the Netherlands in 1575 to celebrate the peace with Spain. M.W.JURRIAANSE, the Founding of Leyden University, Leiden, E.J.Brill, 1965).

[3] (Struik, D. J. 1979, p. 98 & Bos, H. J. M., 1980, p. 19).

[4] (Dijksterhuis E.J. Ch.Huygens. Bij de Voltooing van zij oeuvres, Haarlem, 1951, p.11).

[5] (The term automata nowadays is used in relation to computing and robotics. Nevertheless, from Aristotle until the seventeenth century automaton was equivalent to self-moving. Conrad William Cooke: Automata Old and New, N.XXIX, London MDCCCXCIII, in: Music and Automata. From Horology to Mechanical Musical Instruments. Vol.3, N.9, Sept 1987, pp.81-111. "The word Automaton would in its strictest and most comprehensive sense include all apparently self-moving machines or devices which contain within themselves their own motive power, and in this sense such machines as clocks and watches, and even locomotives and steamships might be included").

CHAPTER 1

HUYGENS' PENDULUM CLOCK

MECHANICS AND ENGINEERING IN THE XVIIth CENTURY

The aim of this chapter is to present Huygens' work on clocks, which were the first to appear with a full geometrical theory[1]. A classification of various clocks is given in a chronological order. All this will show Huygens' outstanding work ahead of his contemporaries and, most importantly, as a forerunner "mechanical engineer". The various models of pendulum clocks, marine clocks and watches, derived from his first and best-known invention, the pendulum clock, which he improved constantly over the years. His pioneering work in mechanics to explain a machine was reinforced by the experiments he designed to calibrate the clock. But, first of all a will present a general introduction to seventeenth century mechanics.

The seventeenth century showed a turning point in the history of applied sciences and it can be argued that this was when the mathematical basis of engineering techniques was developed. This was the case with Huygens' work and instruments. I agree with Usher in that this transformation started as early as the sixteenth century: "The sixteenth and seventeenth centuries mark the transition from complete empiricism to engineering techniques and applied science"[2] and fully disagree with Hall's argument that seventeenth century science "lacked the depth of precise, quantitative information that alone is useful to engineers"[3]. A.E.Musson and Eric Robinson tried to reconcile both views[4]. Pacey argues that the new instruments such as water-pumps, barometers, and, I would add clocks, led to a deeper understanding and communication between mathematicians and artist-engineers and craftsmen: “In the seventeenth century, experience with water-pumps stimulated ‘scientific’ work on the vacuum and on barometers, and Galileo learned much about mechanics in the shipyards of Venice"; the practical arts were influencing ‘scientific method’. The experimental approach in science owed a great deal to people’s growing experience of machines and industrial processes”[5]. Huygens contributed to the new field of mechanical engineering with his inventions and designs of new instruments, collaborating on more than one occasion with the instrument maker or other experimenters.

I believe that Huygens is one of the main figures to bridge the old tradition based in a metaphysical explanation of the universe and the new empirical research based on data to explain new hypotheses and, therefore, with an interest in mechanics ‘per se’. Huygens will show this through the analysis of a specific series of events that led to the development of the various mechanisms and theories that he himself designed, improved constantly and often made. Therefore, the reference to Huygens as an engineer is mainly in the sense of a 'mechanical engineer'. Water works[6] and the military[7] or surveying instruments[8], more mathematical instruments[9], for architecture[10] and tools in general[11], are examples of the engineering carried out for centuries in Europe, or even in Japan[12] and China[13]. Another proof of surviving technology is provided by the Spanish Arab engineers who in the Middle Ages built a system of irrigation still in use nowadays (Valencia, Spain). Later, in the seventeenth century, Italian engineers studied hydraulics of their rivers and lagoons in a way that became highly influential by the beginning of the eighteenth century[14]. However, Huygens was different from contemporary engineers in that his work opened a new field: mechanical engineering. His studies were focused on specific instruments, in particular, precision instruments with a geometrical theory for the first time in the history of engineering.

Therefore, Huygens developed the first treatise in mechanics fully founded on geometry. Following the Archimedean method in geometry, he was able to break with the Aristotelian tradition, which rooted mechanics and physics in metaphysics. With Huygens, mechanics were set on a new path where the laws of nature were explained in a purely mathematical way. Huygens fully developed the idea, supported by some contemporaries, that automata should be accompanied by mathematical explanations. Huygens was the first one to do just that. He explained the clock, the 'automata', as he called it, with the help of a good mathematical basis creating the first book in mechanics: in the sense that the new mechanics were to be the foundations of modern mechanical engineering. On the other hand, Huygens showed more than a passing interest in scientific instruments. He drew them and discussed their construction with instrument makers. In fact, apart from creating the very beginning of modern mechanics, he also maintained a clear and undiscriminating relationship with the instrument makers with whom he discussed his ideas either verbally or with drawings, or any further improvements needed in the instruments. Once the new idea was developed, Huygens explained it to the instrument makers, or drew new improved versions of them. In this way artisans and instrument makers were also able to communicate and influence science when they made a scientific instrument following Huygens' advice and drawings. A good example would be that of Huygens and Coster, the engineer-mathematician and inventor of the pendulum clock and the instrument maker who built the new invention.

Huygens applied the newly developed pendulum clock to marine clocks. His marine clocks are not well known, but as will be seen later, he designed a large variety of models and performed a number of experiments to calibrate them. This will prove further the thesis that Huygens was a forerunner of what later became mechanical engineering.

1 HUYGENS: THE 'MECHANICAL ENGINEER'

Huygens became a well known inventor and natural experimenter through his observations in astronomy, the pendulum clock and the geometrical theory derived to explain it, as well as his various instruments for other fields of science. He combined the theoretical work of the mathematician with the ingenuity of the 'mechanical engineer', giving practical and useful results to his theory. His work was such that he was effectively what later was to be called ‘a mechanical engineer’. Consequently, he became well known not only in the theoretical world of mathematics but also as an inventor and we could consider him under the light of a new type of engineering, that of precision instruments. His reputation, based on mechanical achievements, continued well into the eighteenth century[15]. With this dual interest, he sometimes found that theory did not support his practical work. He created “a new branch of mathematics, the theory of evolutes” in order to improve the accuracy of clocks. Huygens’ work on the measurement of time and longitude at sea according to Mahoney set “a model for a new sort of mechanics, a truly mathematical physics rooted firmly in the physical world"[16].

As the designer of technical inventions he had more control over his own work, and a more direct access to the market. He could sell his inventions that were made by the instrument makers according to his designs[17]. It was the beginning of a new field of science: engineering, in the modern sense of the word, with a theoretical basis from which to develop new and more accurate machines. Although an Archimedean in method, Huygens went beyond geometry to provide the new mechanics with a precise and solid geometrical theory, which could be applied in practice helping in the design and construction of new machines.

It could be argued that some instrument makers could also design instruments themselves. However, this was done independently from the geometry required to explain them. On the other hand, mechanics was a purely theoretical field at universities until the mid-1670s. No machines were described in the texts, nor were they used to explain the principles of statics or dynamics until Rohault's books on mechanics became booktexts at the university.

Huygens worked and united both fields: that of academic mechanics and that of the artisan. He used Archimedean geometry as the theoretical basis to explain the way instruments worked and was easily improved when parts of the device were changed. The 'automata' were explained in mechanical terms, geometry and designs, like the clock or the planetarium. Soon physical instruments followed, such as the air-pump also accompanied by designs. These were explained according to the physical properties of natural elements as understood at the time, to them Huygens added his own theories and those of the atomists. The same method was followed with the optical instruments for which Huygens wrote a treatise on Dioptrics. All the theoretical work, from geometry, to physics, or even optics, was carefully developed to allow the readers to learn how these instruments functioned, how to build them and what results to expect. From then on, technology could be studied and improved in all aspects, practical and theoretical. This allowed the mechanical engineer to make better designs and develop new and more precise technologies. Therefore, Huygens linked also two worlds, the old tradition of mechanics and the modern world of the mechanical engineer, a fusion apparent in his Horologium Oscillatorium (translated by Blackwell, see bibliography).

Sydenham says that a measuring instrument, such as the clock, can be designed with a simple explanation, with words[18]. The first step to describe an instrument is a description with words, then, through drawing, an image represents the instrument, and, finally, a complete design is made with figures and measures, perhaps even perspective. The instrument should be accompanied by general axioms which should underline the relationship between its parts showing a mechanical device working as a hole. The instrument maker will take all this into account when following the drawing given by Huygens. A design for an instrument does not have to be the perfect, working final instrument. In the seventeenth century instruments were based on invention[19] and Huygens belonged to this tradition. Furthermore, the clockmaking trade was certainly well established and Huygens simply explained the changes to the clockmakers, such as Coster[20].

Huygens was an inventor and also a pioneer in having his instruments patented under official protection. In Paris he had the monopoly over his clocks[21]. Therefore, Huygens' design of the clock in the Horologium Oscillatorium of 1673 did not have to work. A drawing was only a guide for the clockmaker who would know which changes to introduce in the clockwork following the accompanying explanation, or instructions from the inventor. This is supported by the contemporary procedure for securing patents. In order to get a recognized patent, the author was required to describe the invention in writing; no drawing was necessary. Therefore, the drawing of inventions were not considered as important as their descriptions which was what was presented to obtain a patent.

It is also important to notice that the intrusion of learned men of independent means into the world of instrument makers was not an extended practice and perhaps that is why Huygens gave Coster the rights to claim the patent. Furthermore, Huygens' exceptional relationship with instrument makers is shown in his recognition of their contributions, and therefore, their right to claim a share on profits that could only be achieved with the issue of a patent. The need to patent a new invention and give the inventor the rights to make it, led Huygens to resort to a higher authority, the Courts of the Netherlands, where an invention could be officially protected from plagiarism. In this way Huygens became the first person to issue a patent to protect the invention of the pendulum clock[22]. Nevertheless, some clockmakers were not satisfied. It seemed an unfair situation that left them without profit for something they were themselves making. These disputes and Huygens' reactions will be considered later.

The mathematical explanation of the invented experimental models was developed in parallel to the improvements introduced in them.

Furthermore, Huygens must have told Coster how the pendulum should be applied to the clock in order to achieve certain results, and the uses it could have. From the first model onwards, both Huygens and Coster worked together to make a more accurate timekeeper. They made the first model of the pendulum clock at the end of 1657.

2 THE MEASURE OF TIME. EARLY PENDULUM CLOCKS.

European clockwork developed after the transmission from Islam[23]. Astronomical clocks were known in Europe through the collected work of Alfonso X el Sabio. He gathered the knowledge of astronomy from the three cultures living in Spain in the Middle Ages: Hebrews, Arabs and Christians creating the school of Translators of Toledo. Of the five clocks described, the clock of *argento vivo* was made up of a wooden wheel supported by a larger one and from which a large weight hung. The clocks could be built to be faster or slower according to the weight used or the diameter of the wheels. There was a variety of this type of clock for use in churches. It consisted of a geared wheel that connected to the main wheel and had an astrolabe incorporated to it. The system was set in motion because the small wheel was connected by a long wooden stick to two wheels of the type described before[24]. This use of wheels and a weight to start the motion of the clock did influence Western horology.

The first historical controversy on the pendulum clock appeared in the seventeenth century. In 1641 Galileo passed to his son his idea of a pendulum swinging regularly, but nothing was done until his student Vincenzio took it up later. In 1669, when Galileo's widow died, it was registered in an inventory: "an iron clock, unfinished, with pendulum, the first invention of Galileo"[25]. Galileo's clock was made by Philip Treffler who also made clocks following Huygens's model, so it would not be surprising to find that Treffler did Galileo's model well after his death. According to Bedini, Ferdinand II employed Treffler as a mechanician and clockmaker from 1650 to 1674. For Bedini Galileo was the first to invent the pendulum clock and Huygens the first to issue a patent for it[26]. Although Philip Treffler made a 'single' copy of Galileo's clock for Prince Leopold de Medici in 1656[27], the fact that it was not fully completed until 1669 is not enough to prove Galileo as the inventor of the pendulum clock. Moreover, Galileo did not design a clock, but a way of keeping the pendulum swinging for short periods of time and this was a development of his work in dynamics.

Huygens worked on the pendulum clock at the end of 1656 and soon developed a theoretical explanation for it. Galileo, on his part, did not attempt to explain in mathematical terms how the clock worked. Another important difference is that Galileo's pendulum was applied to a timepiece completely different from Huygens'. Huygens applied the pendulum to a table clock. We have to remember that longcase clocks did not appear until the 1670s.

Some historians attribute to Galileo the invention of the pendulum clock because he had written to the States General about it, but, this was not made public. It would not be accurate to say that Huygens had access to Galileo's papers in the Netherlands in 1641. Huygens was at that time studying in Leyden. On the other hand, for other historians Galileo invented it because the pendulum clock was described in early manuscripts. But for contemporaries it was Huygens who invented and made it. Huygens was the first to make a pendulum clock and Galileo the first to propose it. In its applications to dynamics Huygens described Galileo's pendulum as a weight suspended from a thin chain. The movement was initiated by hand and the oscillations occurred at equal times[28]. Huygens did not regard Galileo as the inventor of the pendulum clock, but as somebody who had used a pendulum and described how it may work. Who is the inventor: the person who thinks about it, or the person who builds the instrument and makes it work? Furthermore, Galileo did not develop a mathematical theory to explain the clock, whereas Huygens did.

As Brusa states Huygens invented the pendulum clock independently from Galileo[29]. Edwardes defends this view, and like him I also believe that Huygens was the first to develop a scientific and detailed theory of the pendulum[30]. On the other hand, Bruton refers to Galileo's clock as an inefficient and not practical device[31]. At the end of 1656, Huygens finally applied the pendulum successfully, to a table clock. The machinery kept the pendulum going making the oscillations accurate. This was not possible if the hand was used instead. The pendulum clock was further developed and constructed by Coster during 1657 until its final adjustment mid-1657.

Huygens showed an interest for the pendulum as early as 1646, but did not work on it until 1656. It can be stated then that he was the first to apply the pendulum to Dutch table clocks. His aim was to correct three faults already noticed by Tycho Brahe: (a) the irregularity caused by the influence of the seasons upon the clocks; (b) the little accuracy in making the teeth of the wheels; (c) a way to keep a regular weight applied to the clocks[32].

2.1. The pendulum clock from 1656 to 1658

Huygens himself made and applied the first pendulum to a clock on 25th of December 1656. He sent a description of it to Boileau who saw its construction the following April when he visited The Hague. At the beginning of his manuscript of 1658 -manuscript K- Huygens said that it was because of astronomy that he had invented the pendulum clock[33]. At that time astronomers were using a suspended pendulum which was set in motion by hand and was kept swinging by an assistant who also count the beats. Plomp says in that this was a tedious and inaccurate job, especially if the assistant fell asleep[34].

Huygens mentioned Galileo as the 'initiator' of the pendulum, which makes some historians, including the editor of the Oeuvres credit Galileo as the inventor of the pendulum clock. They have misunderstood the fact that Huygens knew about the Galilean definition of isochrony as a natural developement of Galileo's dynamics: "*viro sagacissimo Galileo Galilei, hunc modum inierunt, ut è catenula tenui pondus appensum manu impellerent, cujus vibrationibus singulis dinumeratis, totidem colligerentur aequalia temporis momenta*"[35]. Huygens was referring to the Discorsi of 1638. Galileo was demonstrating a physical concept, which already appeared in the Dialoghi of 1632[36]. Huygens mentioned A. Colvius who had sent him a tract by Galileo; however, Colvius referred to longitude at sea[37]. Therefore, Huygens did not recognize Galileo as the inventor, but as the 'initiator' of the pendulum in dynamics and not to be applied to a clock but to a device that would keep it going. Galileo's pendulum referred to a 'physical' concept of isochrony.

On the other hand, according to Drake a Venetian doctor whom Galileo knew used a type of pulselogium. It would explain why Galileo's pendulum was not intended for timekeeping but to keep the pendulum swinging at regular intervals, for short periods of time. "He discovered the isochronism of a swinging pendulum but wrongly believed that the swing of any given pendulum occupied the same length of time whatever the arc traversed"; it was not until Huygens that the isochronous pendulum was properly defined[38].

Huygens defined the simple pendulum accompanied by a mathematical theory in his Horologium of 1658[39]. A simple pendulum is a "sizzles" mass suspended by an inflexible, weightless thread"[40]. However, in practice, only the compound pendulum can be used for the control of clockwork, because then the impulse to the pendulum is transmitted through a rod. This he finally defined in the Horologium Oscillatorium of 1673[41]. In the compound pendulum the weight and the rod had to be taken into account, both with their own mass.

The pendulum clock that Treffler claimed to have made following Galileo's ideas, had pins and ratchet teeth and a rigid pendulum attached to it. There was no dial in the device and then the unlocking and impulse took place at one end of the pendulum's arc and not at its vertical position which is required for good timekeeping[42]. Huygens described Galileo's pendulum as a weight suspended from a thin chain that begins its movement by hand and where the oscillations correspond to the same number of intervals occurring at equal times[43]. Landes in 1983 said that Galileo thought of a pendulum as a measurer of time "*misuratore del tempo*" because in his view only the length of the pendulum matters and, therefore, the oscillation of the pendulum did not relate to the amplitude of arc[44]. But when he saw that this was not possible he attributed it to air resistance. Although Galileo was right about the air resistance, however, the main problem was the circular arc described by an oscillating pendulum whose weight hangs from a point and so it cannot be isochronous. Therefore, even if Treffler's model is taken into account, Galileo applied the pendulum to a timer, not to a clock[45] (see figure 1 in footnote)[46]. For Huygens, already in 1657, the clock was a timepiece with equal oscillations, which were kept in regular swings, and with the same length of time by the action of the pendulum and he recognized himself as the inventor[47].

Galileo's device was not made public until Boileau[48], on behalf of Huygens, sent a book to Prince Leopold of Medici in 1658[49]. Later, in 1659, Prince Leopold said that Galileo was the inventor. Boileau wrote to Huygens accordingly asking him to send to the Prince a recent clock for the 120 francs he charged[50]. Prince Leopold wanted to see how the clocks differed. Huygens agreed and sent one of his clocks[51] and later Boileau suggested that Huygens should write to the Prince directly[52]. In his letter to Boileau, Huygens denied any knowledge of Galileo's letter to the States General, saying that the letter was about Galileo's invention of establishing longitudes by means of the Medicean Planets. Huygens also stated that nobody before him had created a way of counting the swings of the pendulum before him, and he was right[53]. Huygens explained further to Boileau that his was a clock which kept going for a long time and it did not need a hand to set in motion as that of Galileo[54].

Huygens dedicated his first <u>Horologium</u> 1658 to the States of Holland and Friseland. In the introduction he stated clearly that this publication had three aims. First of all, he wished to spread the use of his invention to others that might live in distant places. Secondly, the need to protect his invention from unscrupulous imitators, as it was the case with Douw. For this purpose, a patent was issued under the protection of the States General in June 16th 1657. Furthermore, he recognized the consequences of his invention once it was available to a wider market. The invention seemed to have had wider effects than he had first imagined. Pendulum clocks could be mass-produced and sold in the market place influencing directly upon everyday life. The society where the instrument had been designed and made for scientific use could also benefit from its invention. Huygens stated that he had done more than correcting the time of the clocks in one village, but that of all villages everywhere[55]. He was well aware of the impact of his invention not only upon science but also on society.

Why was Huygens interested in creating a more accurate timekeeper? Astronomers needed a mechanism that would give an accurate measure of time and also for the determination of longitude at sea. Huygens regarded his invention as useful to astronomers and also because of its applicability for measuring the length of days and for the science of longitude[56]. Latitude was easily found with astronomical observations. However, towards the end of the sixteenth century prizes were offered by Spain and The Netherlands to find longitude. None of these awards were won[57]. In the seventeenth century Spain was still offering this prize. Moray and Chapelain urged Huygens to apply for it[58].

In 1657, Huygens made his first great design on clocks, aided by the clockmaker Coster. He applied the pendulum to the clock so that the escapement wheel became more exact and precise, making the pendulum clock the most precise clock manufactured so far. In 1657, Coster presented the invention to the States General of Holland at The Hague. Huygens had given him the right to claim the patent as long as he remained the inventor. During 1658, there were other clockmakers who claimed new inventions over the clock. This was the case of Douw, clockmaker in Rotterdam, who claimed to have made a different invention and obtained a patent the same year from the States General. Coster and Huygens declared that Douw's device was not such a new invention, because the clocks were not any different from theirs and they took their case to Court. Finally, it was decided that Douw's patent should be granted and Coster and Huygens received one third each of the profits[59]. Although this outcome seems unjust, Huygens' pendulum clock required further changes in order to improve its functioning. Even when the two cycloidal cheeks were applied to the pendulum the length required was still too long and Douw claimed to have invented something to shorten it and, therefore, make it better. His invention gave less trouble and it could be maintained with no cost at all working better than other new clocks in use[60]. The percentage of the profits as stated in the patent shows that Huygens received also an income from clocks made by clockmakers.

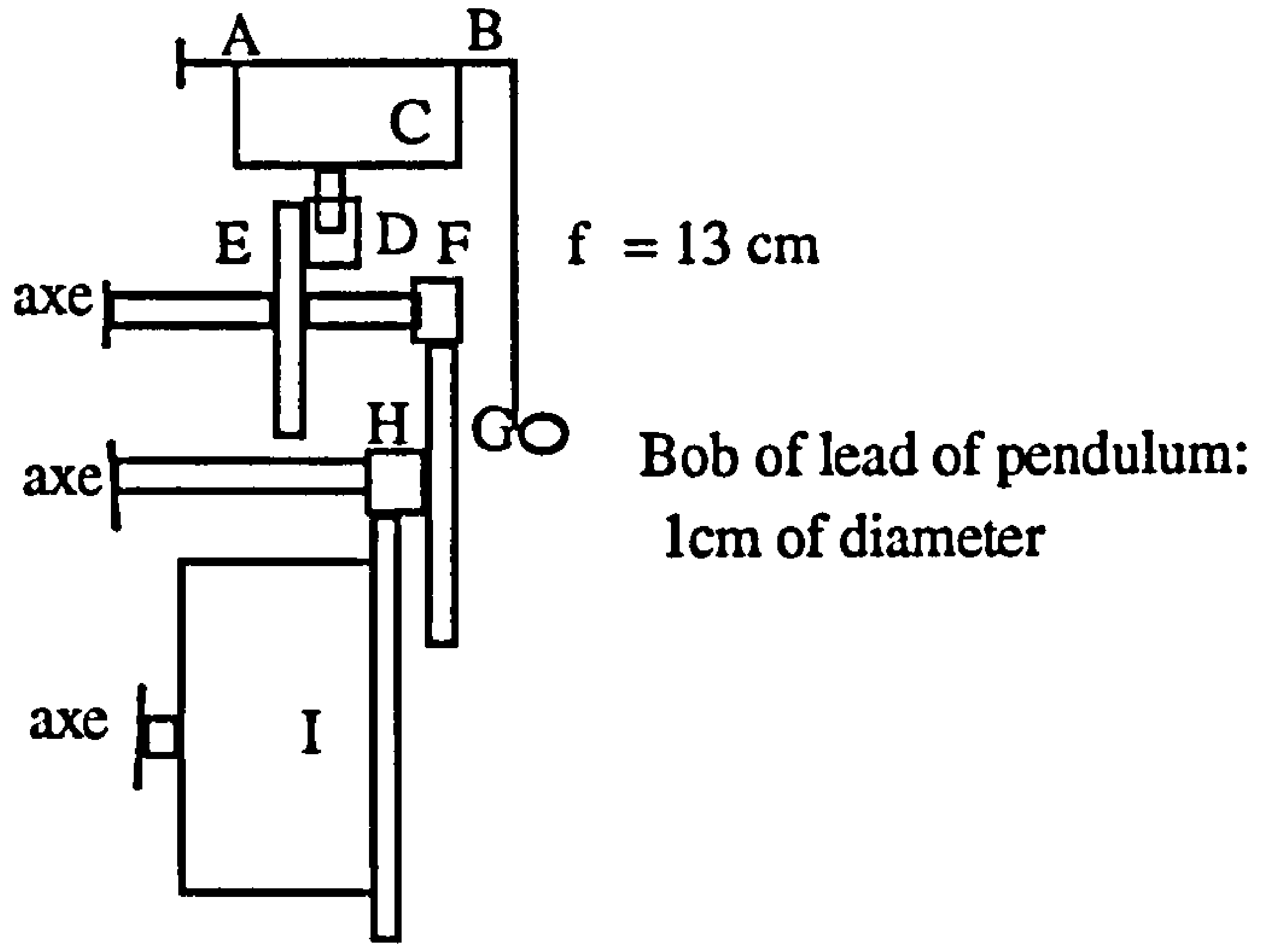
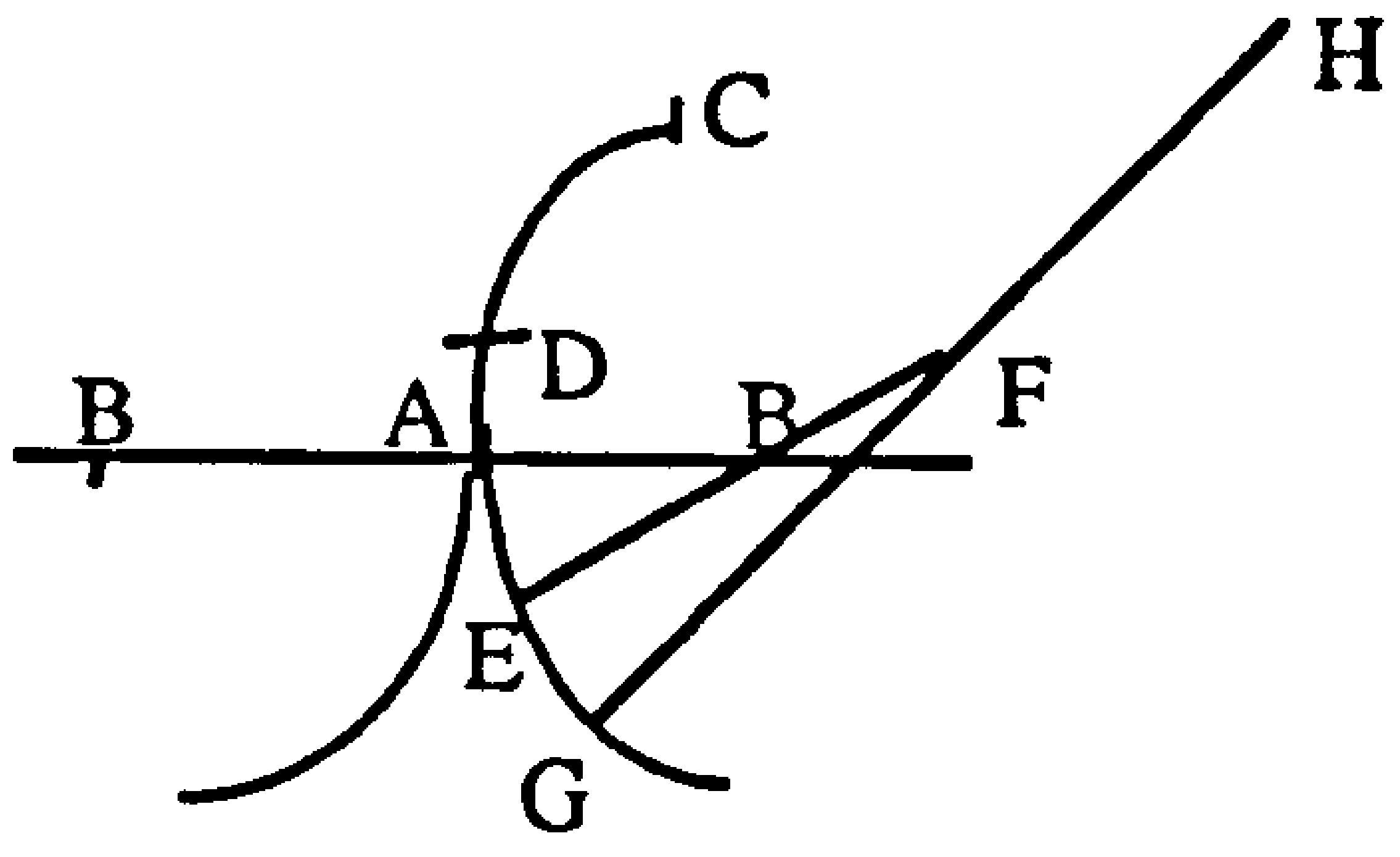


Figure 2. The 1657 design of the clock with two cheeks, the general mechanism appears in the clock of 1673[61].

In 1657, more drawings of cheeks appeared and Huygens' arcs generated a shorter oscillation that those made independently by Coster. This proves that clockmakers were also trying to improve the machine.

Figure 3-The cheeks for the pendulum of 1657: Huygens' (a), Coster's (b)[62].

Until 1657, the pendulum Huygens referred to was a simple pendulum, where the weight of the cord was negligible and the mass was concentrated in only one point. It is only at the end of 1659 that Huygens found the formula for the compound pendulum[63]. There was another problem to be solved: the isochronism of the pendulum, which could only be obtained by applying two cycloidal cheeks to it. At this time Huygens designed the following curve which should be followed by the oscillation of the pendulum (See figure 4).



AC = 1/6 part of the circumference
AD = 1/3 of AC (Manuscript K).
Editor's note: AB = 4,47 cm; EBF = 6,15 cm;
GFH = 18,05 cm
The number of oscillations per hour was of: 4838.4 oscillations. The bob of the pendulum raises 0.072 cm.

Figure 4 – This figure shows the design for the cheeks of the pendulum clock of 1657 and a note from the editor of the complete works[64]. It is not known how Huygens arrived at these values.

Huygens did not give these cheeks much importance, because as he wrote to Petit in November 1658, they still needed improvement. By trial and error he found that in order to achieve more isochrony he had to reduce their curvature[65]. But it was not until 1659 that he applied the cycloid as a shape for the cheeks[66]. In the letter to Petit, Huygens said he had performed the experiment himself. Firstly, he suspended the pendulum between two plates slightly curved, then he observed two clocks set in the same fashion and saw that there was no difference of time after 3 days. He abandoned the idea when he observed that with these cheeks the length of the pendulum changed if the clock was slightly inclined[67]. Maybe because of this experiment he decided to eliminate the cheeks from the 1658 clock. This test was very important to check the accuracy of clocks as measuring instruments and Huygens carried out routine tests also in the 1660s, with any new clock he designed, including marine clocks. The cheeks had been developed empirically and applied before Huygens mathematically deduced the cycloidal ones. This shows once more Huygens as an engineer working empirically on a part of the instrument, the cheeks and the weight of the bob,[68] while, at the same time, deducing the mathematical basis to explain them. By following the mathematical explanation, others would also be able to build the same cheeks. The instrument became reproducible with mathematical precision.

What was Huygens trying to find by suspending the pendulum between two curved cheeks? Was Coster at this point also looking for a better performance of the pendulum to make the timekeeper more accurate? As to the first question, we can say that Huygens was trying to achieve a more accurate timekeeper and, therefore, he was developing an instrument of precision. The answer is 'yes', Coster was also trying to improve the timekeeper but it is necessary to explain this. Huygens was looking for a mathematical solution, whereas Coster was trying to find it only by trial and error, helping Huygens with his idea. This shows how they worked as a team and not as a master and a servant. In order to achieve this, the working length of the pendulum had to be deduced and the thread should not swing around the end of the cheeks at each oscillation. Coster arrived to the same conclusion empirically.

However, the two curved cheeks were not good enough because they did not make the clock as precise as Huygens expected. The two original cheeks had been found empirically and when applied to the pendulum they did not make it isochronous. The shape would have to be obtained mathematically because the pendulum was not isochronous. Only then was he able to find the formula that explained how the pendulum worked: “the time occupied by the swing of a pendulum varies as the square root of the length of its arc, and inversely as the force of gravity”, also known as the "circular error". From this he deduced that if the weight of a pendulum followed a cycloidal path, then “the pendulum was isochronous for all sizes of arc”[69]. Mersenne had already explained what a cycloid was to Christiaan in 1647. In one of the drawings he showed how the cycloid was obtained: "the length of a circumference described when that circumference is rolled, and a point in the latter is followed all the way, the curve described by the point in the air is a cycloid"[70].

Salomon Coster was the first clockmaker to work with Huygens, and was able to work with Huygens changing parts of the clock in order to improve its accuracy. Moreover, it seems that Huygens made his first model of the pendulum clock himself and with one of Coster’s table clocks as he explains to Boileau on a letter of December 1657. He had applied the pendulum to the clock a year earlier[71].

2.2 Description of the 1657, 1658 and 1659 clocks

In his correspondence with the young Christiaan, Mersenne discussed the mechanics of free fall as early as 1646[72], also in 1647[73], and in 1648[74]. Mersenne was already in correspondence with Constantijn, Christiaan's father, discussing different issues such as the fall of the cannon ball, in 1644[75], in 1647[76] and in 1648[77]. Experience always preceded Huygens' deductions in mechanics. Free fall was no exception and in 1659 he outlined the propositions to define it, following Galileo's dynamics[78]. They were expanded later in the Horologium Oscillatorium of 1673[79]. These experiences included bodies thrown, cannon balls, and pendulums and the way to find the isochronism of the latter to make the swing equal at all times[80]. Furthermore, he developed a mechanical method to determine universal measure. He also examined circular force and the bodies that flee the centre developing a concept of centrifugal force, which became standard in the mechanics of the time. Once more, it was reinforced by experience[81]. To this he added a theory to prove that the earth turns[82].

The earliest description of the 1657 clock built by Coster following Huygens' design appears in a letter to Chapelain of March 1658. In this letter the basic principle of how the pendulum works is explained (see figure 5 in footnote)[83]. These years are important dates for the pendulum clock, showing Huygens' engineering abilities. Huygens' designs were not only on models of the pendulum clock, but also some of its parts. The aim was to find the most accurate automaton. A good example of this is all the drawings Huygens made to reduce the amplitude of the pendulum. The fact that the pendulum clock of 1658 was drawn and built with a verge escapement does mean that he did think of other possibilities. These he investigated by experimenting with pendulum clocks where the horizontal escapement was still retained[84].

Huygens thought of a way to improve the pendulum by introducing cheeks at both sides of the pendulum. Although badly defined at first, as the engineer who invents a new part in a design, he improved the model already found through further drawings. These he would have either shown or explained to Coster. This was enough to suggest how the new design would work. This statement would refute Hall's view that engineering was not fully developed because seventeenth century science lacked precision and quantitative information. He misses the point because these developments showed Huygens to be an engineer who designed instruments, machines and parts of these to make instruments or automata[85] more precise. Furthermore, these improvements were normally carried out after trial and error. In general, it is found that the first design does not always work as expected and a modern "mechanical engineer" has to design those parts, which will make the instrument/machine work with more "precision". It is not clear how Huygens arrived at the design of the cheeks for the pendulum. However, it may have been through trial and error that he found the right shape, the cycloidal cheeks, then, he continued his theoretical and geometrical demonstrations[86] and empirical trials to further improve their shape, and Huygens' instruments did not lack precision, at least, for the standards of the time. He gathered quantitative information, which together with his designs helped him to improve the instruments. Better time keeping could be achieved and he created experiments for calibration by testing two clocks together.

From 1657 until 1659, Huygens made several drawings of the verge escapement and tried it in different models. This is a further proof of his determination to find the best mechanism for an instrument of precision. Moreover, Huygens pointed out what was needed in order to build a more accurate timepiece[87].

In 1659, Huygens reintroduced the isochronous cheeks after he derived them with the help of geometry[88]. With the cycloidal cheeks Huygens eliminated the circular error of the pendulum swinging in an arc[89]. Lloyd points out that Huygens applied the cycloidal cheeks to all his clocks and never used the anchor escapement. However, the cycloidal cheeks still introduced error and were abandoned when the anchor escapement was invented[90]. The 1657 pendulum clock had a horizontal verge and two curved cheeks. It was only in December 1659 that Huygens created clocks with cycloidal cheeks. Yoder states that Huygens made two curved plates in 1657 by bending two metal plates to make the path of the bob follow circular arcs[91], to make the pendulum isochronous. This would further prove that he found them experimentally before he developed them mathematically.

Therefore, 1657, 1658 and 1659, were years of experimenting with the clock where some parts were transformed and others removed. He tried two types of main wheels: one totally toothed and another one partially toothed. By trial and error he found that the partially geared one made the timepiece more accurate and he kept it. Most of the drawings, which have come to us might have been changes actually tried in clocks.

Why did he abandon the curved cheeks in 1658? Simply to try a different model during this period of experimentation, because the curves did not make the pendulum as isochronous as he expected. He could not allow the pendulum to lose momentum at both ends of the circular path. He realized with the model of 1658 that the curved cheeks were needed for an isochronous clock. He applied the Archimedean method once more by deducing geometrically the curve the cheeks should have.

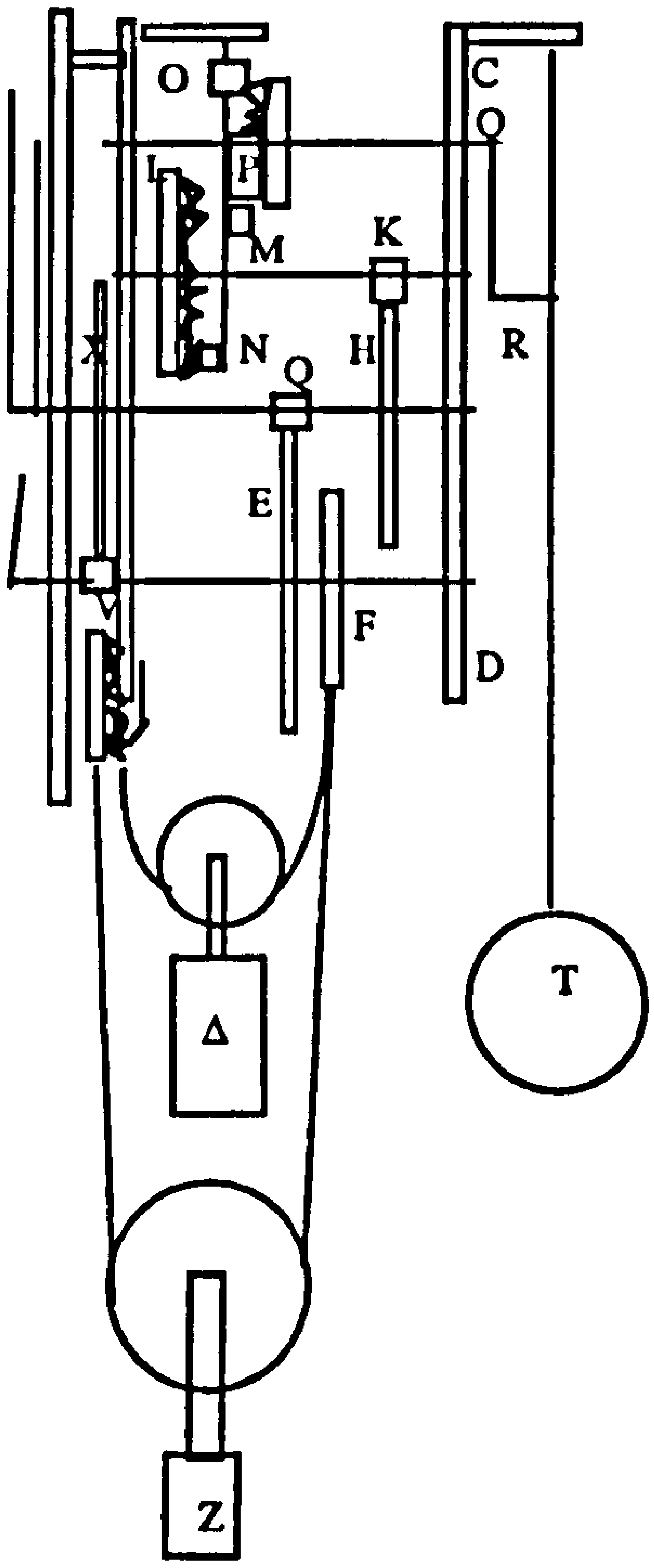


Figure 6- the clock of 1658 with the vertical escapement, a partially toothed wheel (P)[92].

The movement of the 1658 clock was as follows (see figure 6 above). The first wheel E (cogwheel) moved the second wheel F that had a cord around it setting in movement wheel H first and then wheel L, with saw-like teeth. The axis MN, parallel to L, had two palettes that stopped the teeth of wheel L in an alternative movement and rotating it. Axis MN was fixed to pinion O and its teeth stopped wheel P, partially toothed, at regular intervals[93]. The axis of wheel P crossed through plate CD, with a crank, QR, and weight T hanged from the pendulum. T was suspended from S[94]. When the pendulum was set in motion the whole machinery moved. The same principle applied for the 1673 clock.

When the weight was added to the pendulum, Huygens noticed that it slowed it down. He also observed that the oscillations were slower as they drew away from the perpendicular. The two curved cheeks (*platines courbes*) helped to correct this. They controlled these irregular oscillations and once the cheeks were introduced the length of the pendulum also had to be changed (see figure 7 in footnote)[95].

A very important feature of Huygens' clock was his invention of a system of weights connected to the whole machinery by wheels at both ends and chains which drove the clock. These weights were needed to prevent the clock from stopping (see figure 8). According to Usher the weights drove the machinery and also kept the clock in a single position[96]. Weight-driven clocks were already mentioned in the thirteenth century[97]. However, Huygens' weights/chain system survived centuries. There were two weights[98]. One was the primary/driving weight P that prevented the lost of any fraction of time or the pendulum from languishing, while the main weight z ascended[99]. The gravity of the bob T was taken into account giving it a small swing[100]. Weight P was supported by a cord/chain which passed over the pulley D attached to the great wheel, and also over the pulley H, "with ratchet teeth and pivoted to the inside of the clock case". The cord m was pulled down to wind the clock, and the ratchet wheel H ran under its click, one-half of P minus one-half of Z was driving the clock. Pulleys D and H were spiked to prevent the cord from slipping"[101]. This pendulum clock generated the same amplitude of swing unlike previous ones, which had a bigger swing to begin with, and it diminished with time[102]. Huygens was also aware of the action of temperature upon the clock.

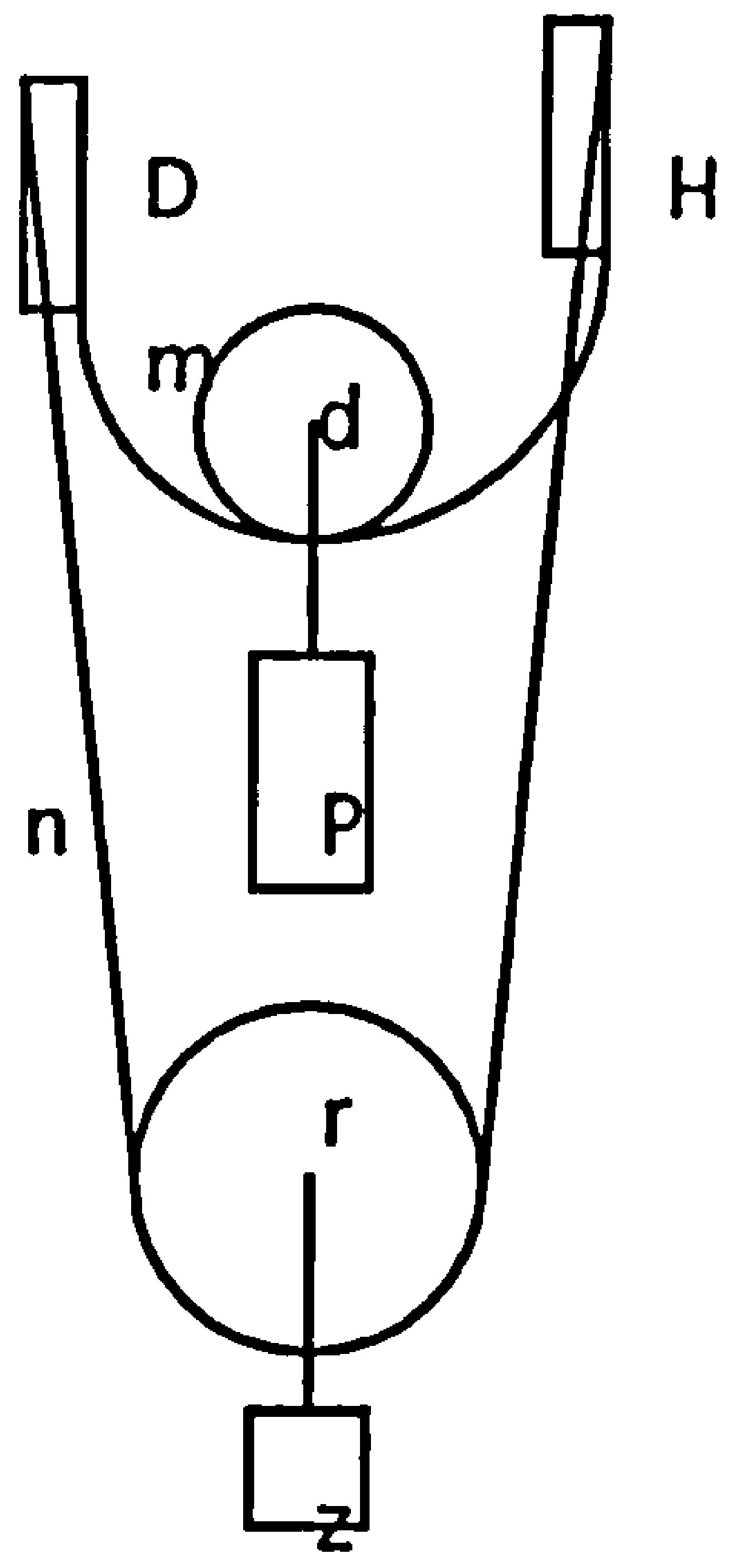


Figure 8 - The pendulum clock was a weight/chain-driven clock.

Before 1658 when Huygens applied the geared escapement to the clock to make the swings shorter and more accurate, two problems had to be solved. The first was a practical problem, the swings of the pendulum were too wide, and it was necessary to find a way to make the pendulum swing at equal times and at shorter intervals. The second problem was theoretical, how to find the distance through which a body falls from rest in one second. Huygens approached the second problem finding the ratio between the time of a fall on the perpendicular of the pendulum and the time of a very small oscillation (see figure 9 below)[103]:

$$\frac{\text{Time over C}}{\text{time over B}} = \frac{\text{length C}}{\text{length B}} \times \frac{\text{speed over B}}{\text{speed at C}}$$

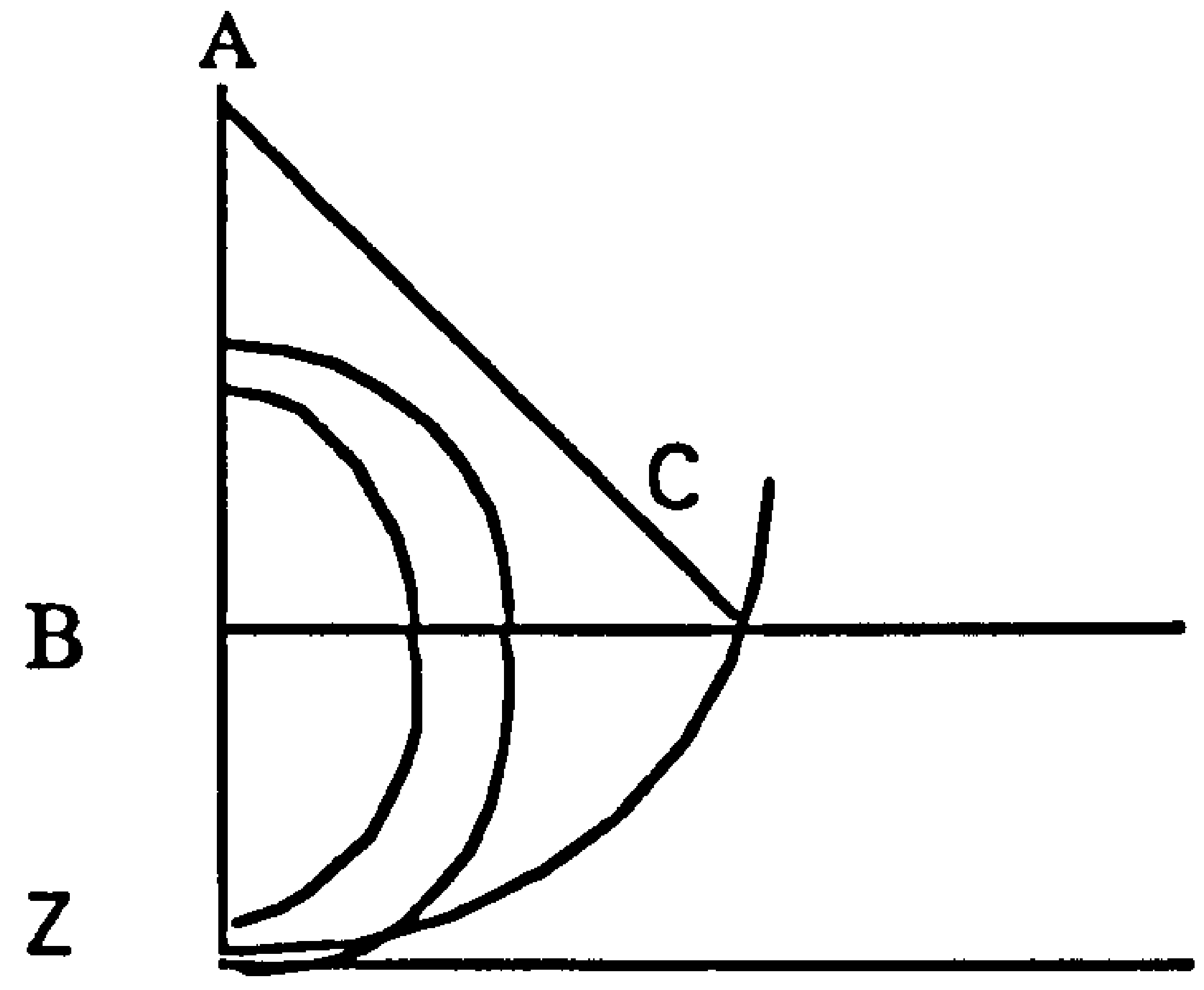


Figure 9 - Time of fall of a small oscillation of the pendulum.

There are four important differences in the pendulum clocks designed and made during the years 1657 and 1658, and which should be seen as a proof of the engineer searching for the best precision instrument. First of all, in 1657 the pendulum clock had a horizontal escapement, however, when Huygens wrote the 1658 treatise it was changed to a vertical one. The second difference is the badly defined arcs of 1657. In 1658 he found, empirically, a shape for the cheeks. Thirdly, the clock of 1658 had 3 hands, whereas that of 1657 had only two and the pendulum of the clock of 1658 made a single oscillation in one second[104]. In the Horologium of 1658 Huygens mentioned Godefroy Wendelin who put forward the idea that time could be measured with swings if they remained constant[105]. Huygens referred to the clocks as automata[106] and as machines[107].

To this experimentation his mathematical work should be added. Theory and practice went hand in hand. He developed a comprehensive theoretical and mathematical foundation to the empirical work on the clock. He attributed to Coster the invention of a spring[108]. Proof of Huygens' experiments with the clock can be found in his correspondence[109].

Therefore, during 1658 Huygens designed different variations of the pendulum clock without the cheeks. The main differences apart from not having the cheeks, was the two different cogwheels, one fully toothed[110] and another one partially toothed which he had found by trial and error, thus making the clock more precise[111]. According to the editor the former was an older design[112]. In my opinion, it is not how early one or the other were discovered, but the fact that he was trying to find the best working one, by drawing each part and by accompanying these designs with the geometry to explain them. Huygens was an engineer improving different parts and choosing what he thought would improve the clock.

In 1659 he wrote to van Schooten about the improvement observed after applying the cheeks[113]. Some authors believe that he simply left the work of 1657 only to pick it up again in 1659. However, he was also creating different clocks such as the conical pendulum clock of 1659[114], which in 1674 he said he had already invented in 1658[115]. Unlike what some historians have stated, Huygens continued working on the clock, only because he had not designed a totally different one. He was simply working on those parts he thought had to be improved and the theory needed to explain the clock which was developed in several treatises before 1673, i.e. <u>De Vi Centrifuga</u> of 1659[116].

The years 1657, 1658 and 1659 were very important for experimenting and designing the clock. Contemporaries got to know about the new innovations very soon and wanted to see the latest clock, or have it sent[117] or simply ordered one[118]. They asked Huygens for advice for building their own clocks[119], or how to use his properly[120]. The year 1659 was especially important because Huygens' European colleagues wanted him to explain the problems they had understanding how the new clock worked[121] and many of Coster's clocks were tailor-made following the indications of the buyer[122].

2.3. The conical pendulum of 1659. The cycloidal cheeks (1659-1661)

It was in 1659 that Huygens developed the cycloidal cheeks geometrically. It was a period of further experimentation and trials. He introduced the cheeks again after deducing a mathematical demonstration with which he found the proper geometrical figure. Huygens then demonstrated the theory of evolutes and discovered the isochronism of a cycloid[123]. It was in 1659 that the clock with cycloidal cheeks appeared and also its drawing and book.

In 1657 the cheeks made the amplitude too wide. In 1658 Huygens had decided to eliminate them and try to find something else in the pendulum which would reduce the arc of oscillation by changing to the horizontal geared escapement and, in 1659, he designed conical pendulums for the same purpose[124].
Huygens applied the fall of a body to the pendulum and found the distance traversed by a falling body from rest in one second. He worked on the free fall of bodies from February to December 1659. The velocity of the weight of a pendulum at B was such that it allowed it to reach a height, BC if it was free, and this height was proportional to the square of its speed (see figure 8 in footnotes and 13 below)[125].

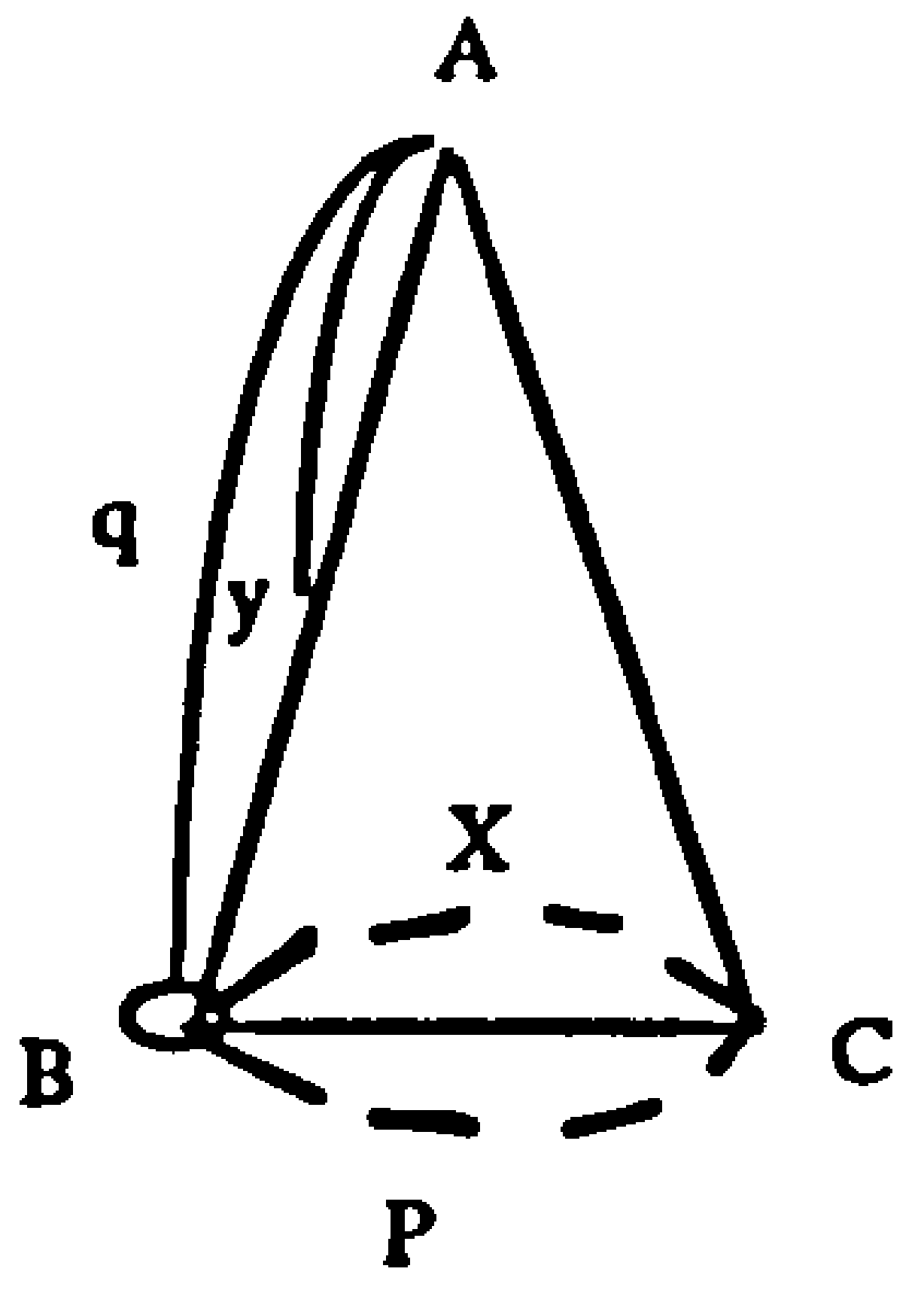


Figure 10- the fall of a body applied to the pendulum.

Huygens compared the simple and the compound pendulums, which he calculated empirically[126] $py = qx$ (see figure 10). The angular velocities of the point B and that of the isochronous pendulum reach a height proportional to the speeds they possess at the lowest point and are proportional to the square of their velocities[127]. Therefore, Huygens went further than Galileo, who had worked on falling bodies, by applying it to the oscillation of the pendulum[128].

In December 1659, Huygens deduced the cycloid mathematically[129]. With the cycloidal cheeks, the oscillations of the pendulum took the same time. Mahoney calls it the tautochronic pendulum[130]. Huygens added to the cycloid the kinematics of the ratios of the chords generated by the cycloid. Near the centre line, the pendulum acted as a simple pendulum of known length. But for wider amplitudes, the simple pendulum swung with a different centre from the point of suspension[131]. With the cycloidal cheeks the cord of the pendulum followed the curve they described, the parabola, shortening the swing of the pendulum and making it isochronous. With these curves at each side, the bob remained perpendicular to the pendulum up to the last point of contact with the cheeks. After the cycloid many other curves could be described mathematically. Huygens opened up a new field: mechanical engineering and in mathematics: algebra.

Another model was the conical pendulum clock where the bob of the pendulum [A] was compensated with a bob of lead [E] (see figure 11 below):

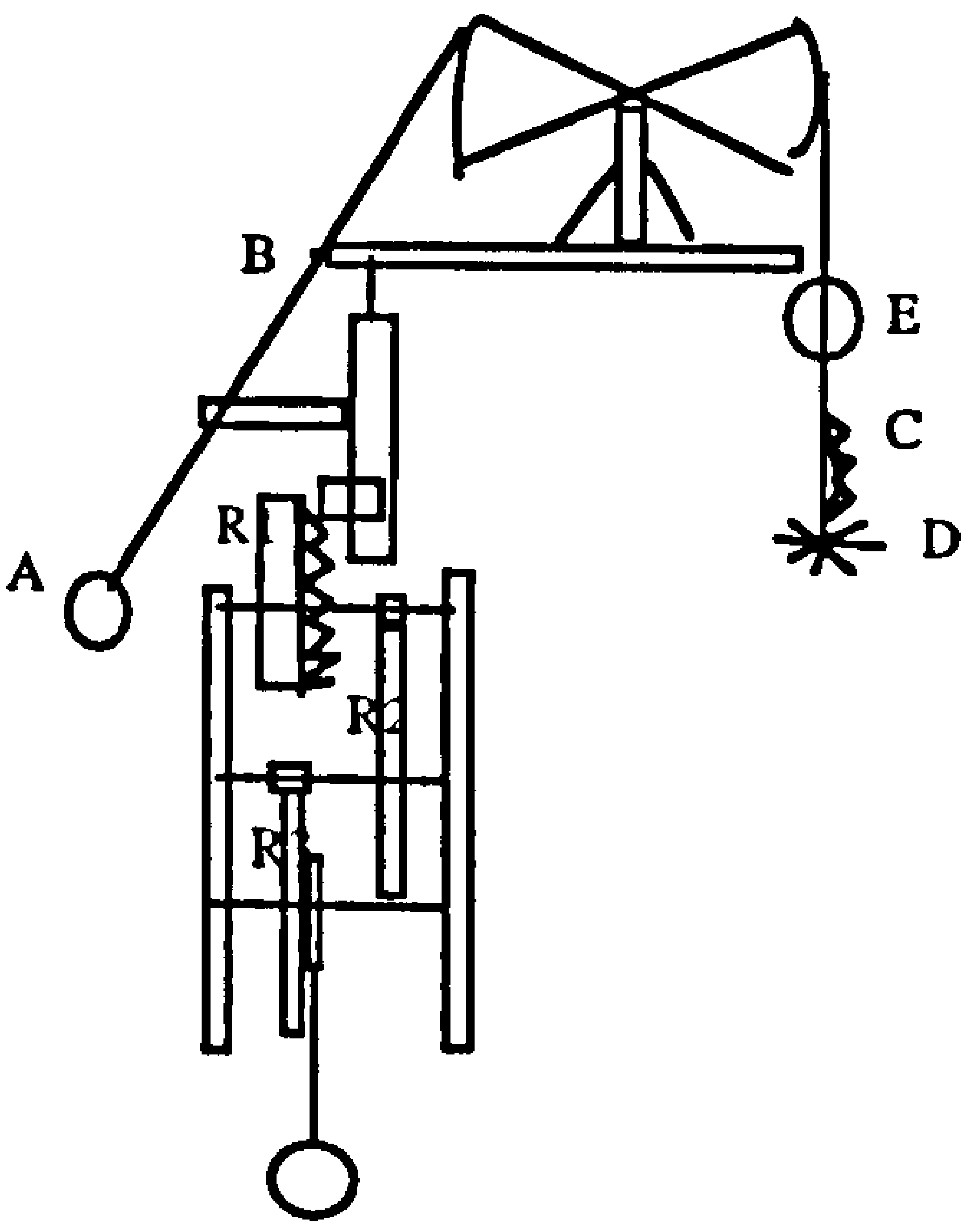


Figure 11. The conical pendulum of 1659 with a hydraulic piston.

In the conical pendulum of 1659 (see figure 11), AB was in equilibrium with weight E and both were linked by a cord passing over a pulley. The chain CD hung from E, the weight A was light so that if the length of AB diminished, the weight E descended and CD needed to be adjusted. The length of AB could be reestablished with weights to raise weight E. The weight A rotated circularly around the clock. There was no constant rotatory movement. The main aim was to maintain the length of the cord AB because as soon as it changed CD would vary. At

B there was a horizontal force exercised over the cord. In order to maintain the balance between A and E, the chain CD had to be adjusted. Huygens used a chain (CD), or a cylinder of mercury moving inside a second cylinder also filled with mercury, a hydraulic piston, see below:

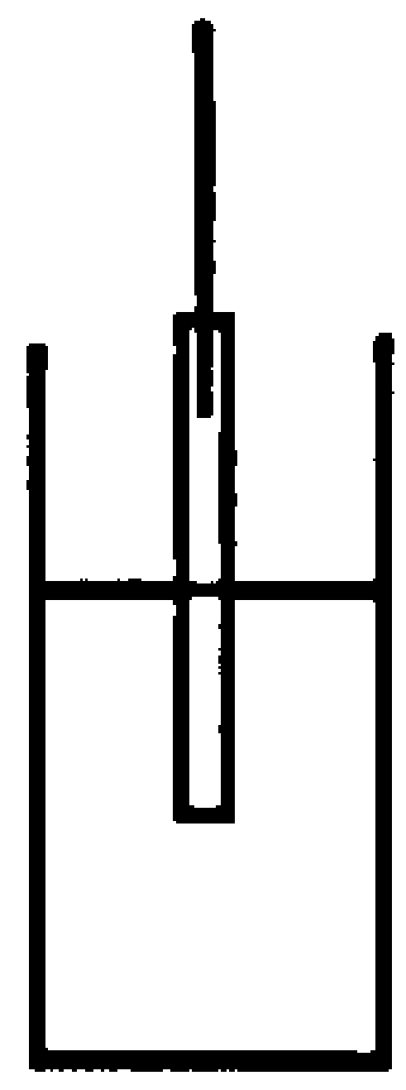


Figure 12. Hydraulic piston of the conical pendulum of 1659 with water or mercury[132].

The aim was to balance the tension with the weight and the cord CD in the hydraulic piston and then other weights were added to A[133]. Although Huygens did not know how to keep this system going, however, he must have mounted the conical pendulum on some kind of device because of the number of calculations given. Like Yoder[134] I believe that this clock must have been made and tried by Huygens, contrary to the editor of the Oeuvres who states that this must have been a design and was never built[135]. There seemed to be a pattern in his work by which, he drew what he thought needed to be changed and applied to the automaton. Further proof of all this is the fact that Huygens accompanied this drawing with measures and the number of turns of each wheel of the clock multiplied by the number of teeth and by the time and so on with all the other wheels. From then on he worked out the revolutions per hour and the acceleration of gravity per second. How he arrived at the length of this pendulum is difficult to know[136].

By December 1659, Huygens had worked out the cycloid, which from then on became the path the cheeks of the clock should follow to make it isochronous[137]. To derive the cycloid, Huygens compared the fall of the bob of a pendulum in a small circular arc, to the rectilinear fall of a body following a height equivalent to the point from which the bob began its fall to the central point where the small arc ended (see figure 13).

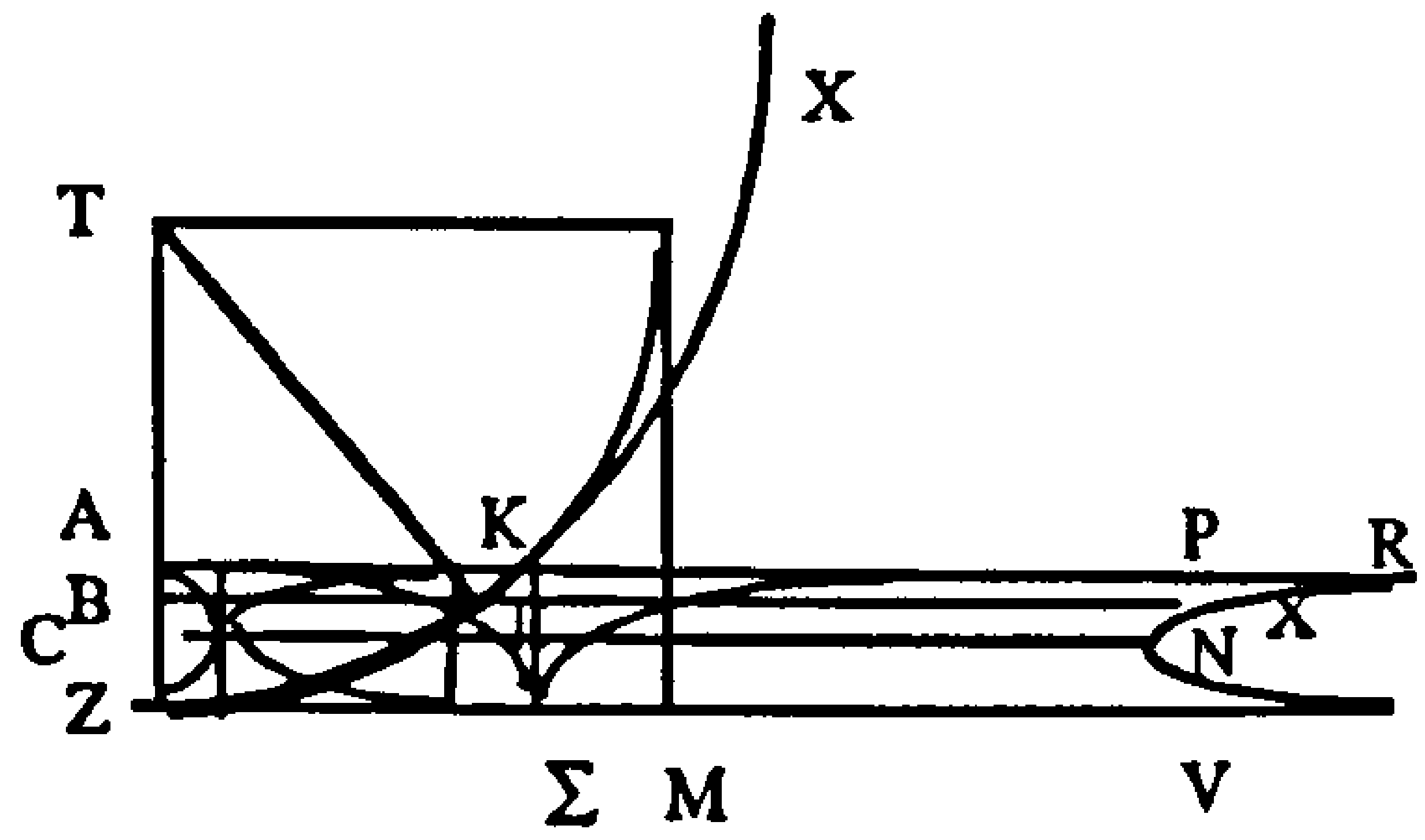


Figure 13 - The cycloid, 1st December 1659.

Huygens resolved the problem of the isochrony of the pendulum when he tried to find the ratio of the time that would take the bob of a pendulum to fall a minimum oscillation (figure 13, minimum oscillation: KZ) and the time that would take for a body to fall vertically (figure 13, vertical fall: AZ)[138]. E was an infinitely small arc of KZ. Huygens compared then the time that would take the bob to fall an infinitely small arc E, of the arc KZ, with the time a body would take to fall an infinitely small part on the vertical fall AB, from AZ, and both motions began from zero velocity[139] and wrote:

$$\frac{\text{infinitesimal at E}}{\text{infinitesimal at B}} = \frac{TE}{BE}$$

Huygens used Galileo's propositions on motion on an inclined plane from the Discorsi[140]; the vertical distance fallen, AB, was proportional to the square of the speed. So that he was able to represent the speed of fall graphically, also for the parabola. The velocity (v) acquired at Z was represented by $Z\Sigma$ (=AK). A uniformly accelerated body falling from A acquired a velocity, v, which also represents the speed of the body on the vertical fall AZ[141]. Huygens did not know the algebraic notation of the constant of gravity, which would have simplified his derivation. Instead, he used geometry and centrifugal force. Huygens drew geometrically accelerated motion as a parabola of fall ($AD\Sigma$)[142]. From Galileo's propositions Huygens knew that the time of vertical fall (from A to Z) of a body with uniform velocity was half the time it would take to fall from A to Z under the force of gravity[143]:

$$\frac{\text{time of gravitational fall through KZ}}{\text{time of gravitational fall through AZ}} = \frac{\text{infinite space APRXNHVZA}}{2\,AZ\,.\,Z\Sigma}$$ [144]

Huygens proved geometrically what Galileo had said, that for small arcs the oscillation was isochronous[145] and found the value of the ratio of a body following a circular path to one on free fall. Yoder has summarized the final equation[146]. Therefore, the circular path described is isochronous because the time through TZ is constant and the time of fall of the bob of the pendulum following KZ is also constant[147]. In order to be able to apply this isochronism to the cheeks of a clock, he worked on the theory of evolutes[148].

The way Huygens designed the cycloidal cheeks is reminiscent of an engineer at work because he chose the materials, the design and the mathematical theory to explain them. He went further, and designed his own model[149]. It had to be very easy for Coster to apply it later. An example of this is found in 1660 when he made some designs for the clockmakers to build. This design of 1659 had a note saying: "say to the clockmaker to move the hand of seconds through the winding wheel. And to enlarge the big wheel and talk to him about the small weight pulley"[150]. Huygens used Galileo's dynamics, for instance, his definition of the product of the length of the pendulum by the square of the number of oscillations as a constant at a given time. These calculations appeared regularly with most of Huygens' designs. This further proves the statement that Huygens' pioneering work in "mechanical engineering" was unique to the time since drawings were accompanied by mechanical calculations. Furthermore, it shows one more quality of Huygens' pioneering work, that of knowing what specific part of the mechanism had to be improved, and how to calibrate it.

R.S.Westfall also defines Huygens' derivation of the period of the conical pendulum. According to Westfall, Huygens had the ability to relate the period of the conical pendulum as a function of the acceleration of free fall and the period of the ordinary pendulum as a function of the same value, equal period for minimal oscillations. In both pendulums, periods varied as the square root of vertical height[151]. As Westfall says, it was clear that Huygens never used the concept of gravity as '*gravitas est conatus descendi*'[152]. Weight and centrifugal force were equivalent terms for Huygens[153]. *Vi Centrifuga* was defined as a radial force[154], which varied with the diameter of the circle for the same angular velocities and was proportional to the square of the velocity for equal circles. The periods for equal bodies with equal linear velocities on unequal circles, and equal centrifugal forces varied as the square root of the diameter[155].

Huygens defined the conditions of the centrifugal force by using

Galileo's fall of bodies. Following the path described by a body in circular motion when describing the circumference of a circle and with the same velocity that it would acquire in falling through half its radius, the centrifugal force would be equal to its weight. The units were established, and from Galileo's formulae for free fall, it was easy to derive: F=mv/r[156].

With the isochronous clock, Huygens was able to calculate the value of g with one oscillation and it is found in De Vis Centrifuga, which was a preparation to the Horologium Oscillatorium of 1673[157]. In December 1661[158], Huygens wrote to Moray about the cycloids not providing a perfect isochrony for the pendulum. He attributed this to the action of air and substituted the cord of the pendulum by a chain, but without success. In his answer, Moray said that the air could not really have any effect on the clock[159]. When Huygens found the centre of oscillation for the pendulum[160], he concluded that the cycloidal cheeks could only make the simple pendulum isochronous, but not the compound one. With Mahoney and Koyré I agree that Huygens found the isochrony of the pendulum through the ratio of the time of fall along the cycloid and the time of fall along the diameter of the circle that generated the cycloid. These times kept a ratio equal to that of the semicircle and the diameter[161].

In June 1658 Huygens said that it was possible to determine the longitude applying the pendulum clock[162] and his contemporaries agreed[163]. This interest was more obvious during 1660 and 1661, when Huygens started new designs on marine clocks. Some designs included a project of a marine clock with a heavy receiver at the top of the cheeks and the pendulum. The editor of the complete works says that the function of the heavy receiver was to keep the clock in a vertical position at sea. He worked on the centre of oscillation of a simple pendulum in isochrony with a compound pendulum[164]. Also in 1661 and until 1666[165], Huygens was working in the centre of oscillation for the simple[166] and the compound pendulums[167]. The same year Huygens drew clocks with a geared horizontal escapement of 30 teeth. He added some notes for the clockmaker to make the appropriate changes[168].

Although busy with the air-pump, from 1660 to 1664, Huygens was preparing the treatise of the pendulum clock. In April 1660 Huygens wrote a summary of an amplified edition to the 1658 treatise on the Horologium[169]. This second edition he had mentioned to Boileau[170] also to Moray saying that he intended to improve the clock[171]. He had introduced a new change in the clock and wanted to keep it secret for the moment[172]. During 1664, Huygens was also working on evolutes and on the value of g[173].

3 THE PENDULUM CLOCK OF 1673. LONGITUDE AT SEA AND LATER CLOCKS

3.1. The Horologium Oscillatorium of 1673

In 1664 Huygens had applied a sliding weight (cursor) to the verge of the pendulum for the first time. It helped to adjust the clock. He worked on the compound pendulum with two weights[174]. He defined how it worked and its function in the Horologium Oscillatorium. The diagram represented a cursor weight C in verge AC (see figure 14).

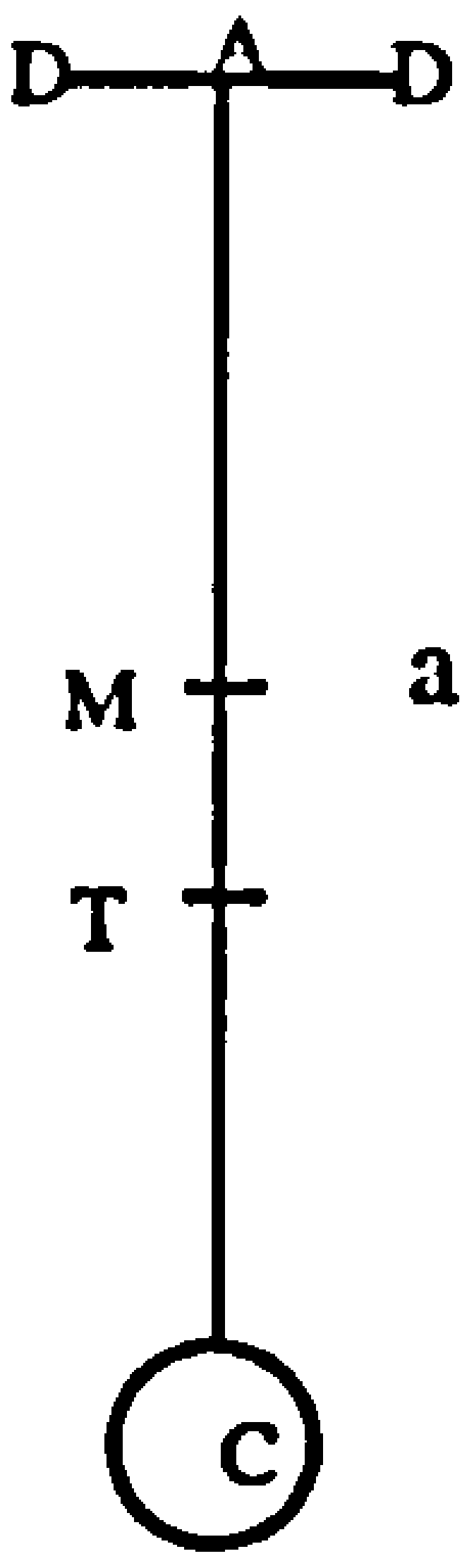


Figure 14 -The simple isochronous pendulum of 1673[175].

First of all, he found the length of the isochronous simple pendulum with a known length of the verge AC, a, divided in many equal parts. Let M be the centre of the segment AC and its centre of gravity and T the centre of gravity of the plane perpendicular to AC passing through T, such that AT = 2TC. It was also known that MA = 1/2 a and TA = 2/3 a. The addition of all the distances in AC to the point A was equal to 1/2 b a, by half the number of the particles at each point where the verge was divided. In TAM, $1/3\ a^2b + a^2c$ was the addition of all squares (those from the verge and from point C). The addition of the distances of the particles of weight C to A was ac. Therefore, the length of the verge of the pendulum was easily found by dividing the addition of all distances: $1/2\ ab + ac$ by the first one:

$$\frac{1/3\ a^2b + a^2c}{1/2\ ab + ac} = \frac{1/3\ ab + ac}{1/2\ b + c}$$

Furthermore, to find the length of the compound pendulum (figure 15), Huygens studied a new verge: AC with the weight C suspended at the end of it and another weight, D, was also added. The distance AD was called f, and d was the number of particles from D. In order to find the simple pendulum which should be isochronous with the compound one, he took into account the distances to A from D, dff. The addition of all the squares was: $1/3\ a^2b + a^2c + f^2d$. These had to be divided by the addition of all the distances of the particles of weight D: $1/2\ ab + ac + fd$, the final formula being:

$$\frac{1/3\ a^2b + a^2c + f^2d}{1/2\ ab + ac + fd} = p,\ \text{the length of the pendulum.}$$

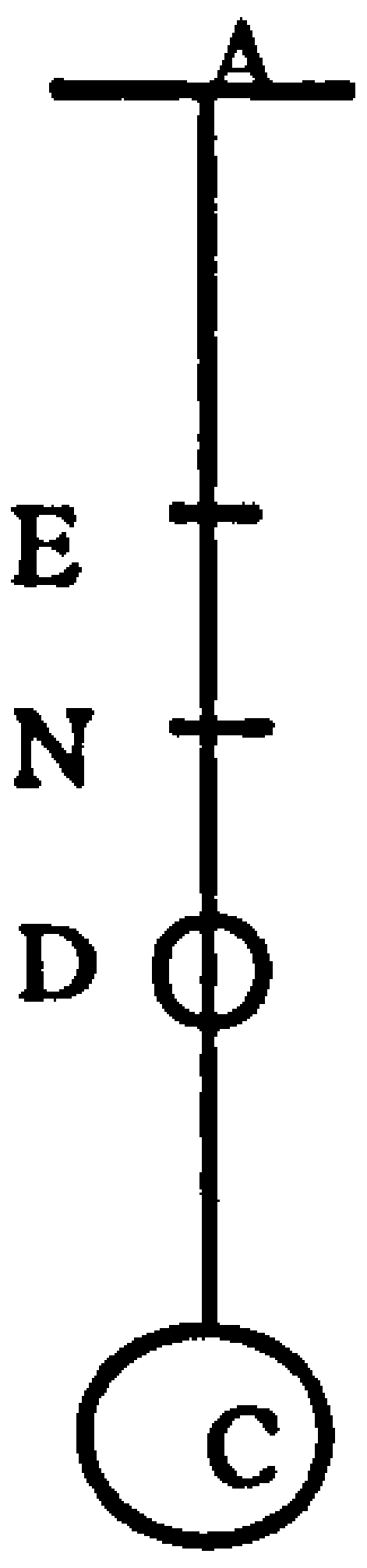


Figure 15-The compound pendulum with bob C and cursor weight D[176].

By getting f^2 out of the equation given above, it was finally deduced that

$$f = a/2d\ \sqrt{4/3\ bd + 4\ cd + b^2 + 4bc + 4\ c2 - (ab+2ac)/2d}$$ [177]

This formula determined the distance of the cursor weight D to point A accelerating the movement of the pendulum if necessary[178].

dedicated to Louis XIV. In the preface he expressed his gratitude for the king's generosity and said he was happy to have invented the clock during that reign. The king had recognized how useful the clock would be for the state and the public, and how he had fostered in his Court the most advanced sciences and inventions[190]. The king had several clocks made by Huygens in his own palace[191]. The French-Dutch war of 1672 did not seem to stop Huygens from praising the very king who was at war with his country of origin. Furthermore, he wanted to name the Saturn satellites, discovered while at The Hague, the "Bourbons Stars"[192], in the same way as Galileo had called Jupiter's satellites "Medici's Stars", to praise his protector, the Grand Duke of Tuscany.

A detailed side section of the pendulum clock, the cycloidal cheeks and a weight driven clock with a pendulum as it would look hung vertically (figure 16) precede the preface[193]. He stated the use of the pendulum clock for astronomical observations, for measuring longitude at sea and for the public in general[194]. Huygens stated that he had found a different and new way of suspending the pendulum, through geometry: a curve to give the pendulum the right swing[195]. This curve was called a cycloid and allowed to measure time more accurately. The drawings of the automaton were accompanied by a mathematical theory deduced with Archimedean geometry.

Huygens emphasized the importance of this mechanical construction and how his explanation would allow others not only to make it, but also to modify it. Huygens did not find the curve traced by a compound pendulum, but he knew that it was necessary to determine the centre of oscillation of geometrical figures[196]. He pointed out the fact that he had made the pendulum clock himself, without any influence and this was unquestionable. He had also been the first to transfer the simple pendulum to the clock, with the addition of the cycloid. He questioned the defenders of Galileo who attributed to him the priority over the pendulum clock[197]. The treatise of the Horologium Oscillatorium was composed of five parts.

Huygens described in the first part how the pendulum clock worked. Figure I was a side section of the clock and the pendulum. Figure II was a three-dimension design of the cycloids, figure III was the clock hanging on the wall and figure IV was a series of measures to show the position of the wheels in the clock and the centres of oscillation of the pendulum (see figure 16). These drawings show a pioneering work in mechanical engineering that became standard later on. Huygens provided the different parts of an instrument, its measurements, as well as a cross-section of it in figure I. The cycloids, found in figure II, were essential for the accurate running of the clock. The whole clock was also drawn as a working model in figure III. Furthermore, the dimensions of the clock were given in figure IV and this had not been seen in previous automata, but became essential afterwards in any design of machines or inventions (see Figure 16[198] in attached page).

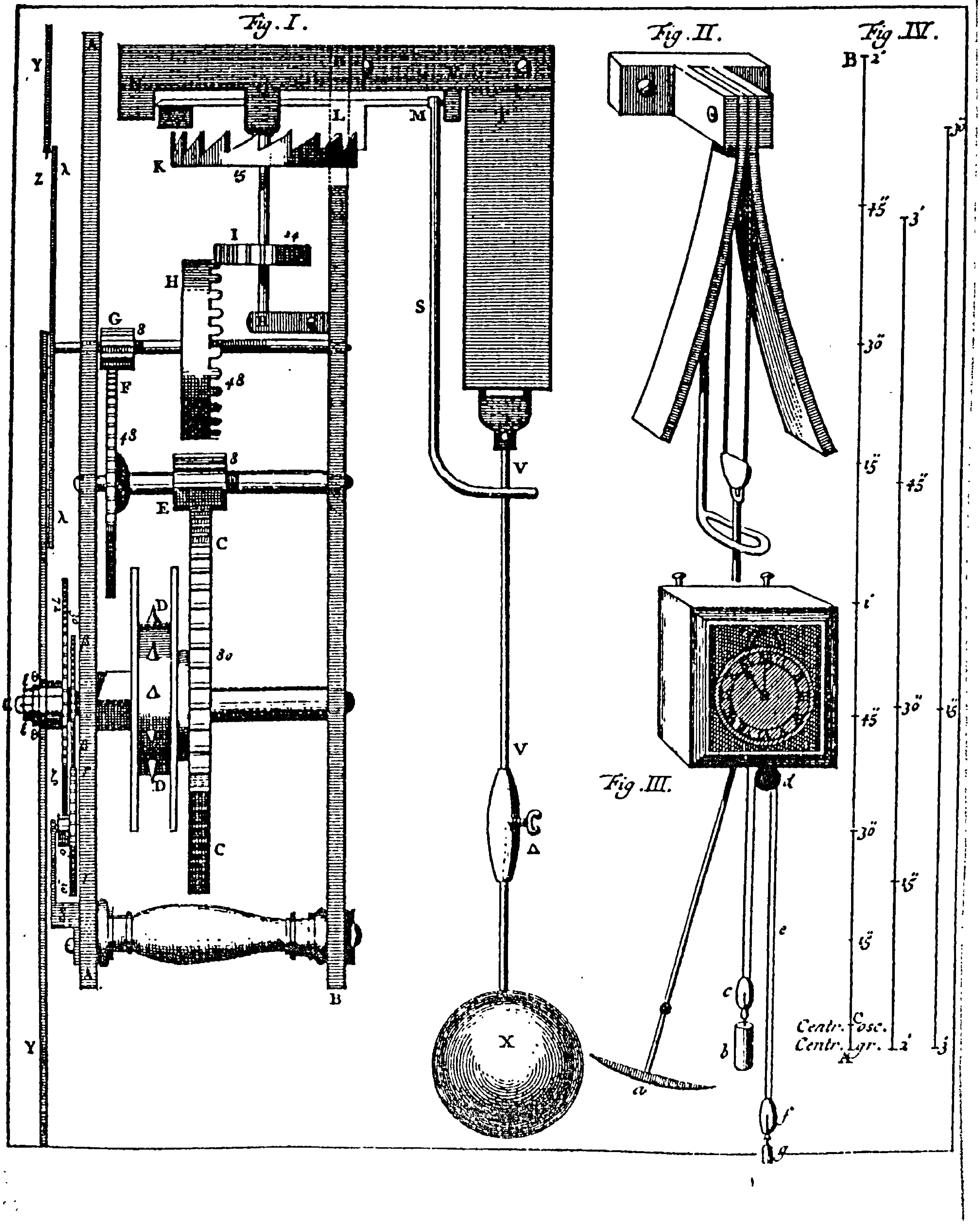
The way the clock worked was described following the 1658 treatise. AA and BB were two plates that held the main axis of the wheels. The first wheel, at the base, was C (80 teeth) and an axis fixed to the pulley D, with spikes to hold the cord/chain of the weights. The weights drove the clock moving wheel C which communicated the movement to the cogwheel (pinion) E (8 teeth). In turn the latter moved wheel F (48 teeth) attached to the cogwheel G (8 teeth) which then transmitted the movement to the crown wheel H (48 teeth); its teeth moved the cogwheel I (24 teeth) and the fixed wheel K (horizontal escapement) had 15 saw-like teeth. Over K there was the horizontal verge with a palette at each side and they alternately stopped wheel K at each oscillation of the pendulum (three French feet long) which was set in motion by the hand[199]. This movement was regular and constant so that each oscillation moved the horizontal verge and each palette each time, at equal times. The weights kept the machinery going, the pendulum was the regulator of isochronous oscillations. The construction of all the wheels had to be precise, otherwise the clock did not work. The weights weighed in total six French pounds. It was a weight driven clock already described in 1658 and admired by contemporaries[200]. Huygens kept the quality and the precision in the construction of all parts of the clock.

The second and most important part of this treatise was the study of the cycloidal cheeks. He explained how he had deduced them experimenting with cords and bobs of equal length and weight, respectively, to see how this would affect the amplitude. By giving a different initial impulse to the bob of two experimental pendulums, he found that the smaller the oscillation the longer it lasted and the more regular it was kept. The application of the cycloidal cheeks applied to the pendulum kept it isochronous[201]. Then Huygens worked out the length of the pendulum, knowing that the length was in proportion to the square of the period[202].

The cycloid could be easily drawn (figure 17 in footnotes). First of all, a circle with a diameter equal to half the length of the pendulum moved over a rectangular plane (AB) with a band attached to the plane. In the circle a point was chosen (I) as the circle moved over the plane a curved line was described, this was the cycloid[203]. According to Huygens this curve had a property that was unique to it. When a pendulum was

Figure 16 – The pendulum clock of 1673 (Vol.18, p.71).

[Fig. 17.]



suspended between two cycloidal cheeks, the path described by the oscillation from beginning to end was another cycloid[204]. He also described another way of finding this curve[205].

Once the clock had been built, it was necessary to calibrate it. One method consisted of comparing the time given by the stars in the traditional way, or by the sun. Huygens showed that the latter was best if using the table of the equation of time[206] and adjusting the clock finely with the cursor weight[207] according to the difference found.

In the second part, Huygens deduced three hypotheses of the movement of bodies with and without the action of gravity[208]. These hypotheses were equivalent to the principle of relativity. They were followed by six propositions on the properties of the free fall of bodies, with ratios between speed of fall, spaces fallen and time[209]. From there, Huygens deduced the movement of bodies along inclined planes[210], developing further Galileo's propositions and finding the relation between the fall through inclined bodies and free fall (see figure 18 in footnote)[211].

Huygens applied the geometry and mathematical ratios found in free fall and the cycloid[212] to circular motion[213]. He drew tangents to these curves and found the ratios between them[214]. Then he drew a series of tangents to a semicircle and the perpendicular from the tangents to its diameter[215]. He then applied the ratio between the tangents to the curve and the circular movement of a body in it. He related the movement along the tangents to the geometrical ratios found with the inclined planes[216]. Huygens deduced how a body behaved when following the circular path. He stated that the time it took the body to descend along one of the least inclined tangents to the circle was shorter than in the most inclined ones. Then he found the ratio between free fall and circular motion in a pendulum[217].

In this proposition, Huygens deduced the ratio between the time that took a body to descend through a cycloid (BE) and that through a tangent to that cycloid (BI), with half the velocity acquired falling down the tangent (B©) and it was proportional to the arc of the circle which formed the cycloid, to the diameter of that circle in the point chosen to end the fall (FG) (see figure 19).

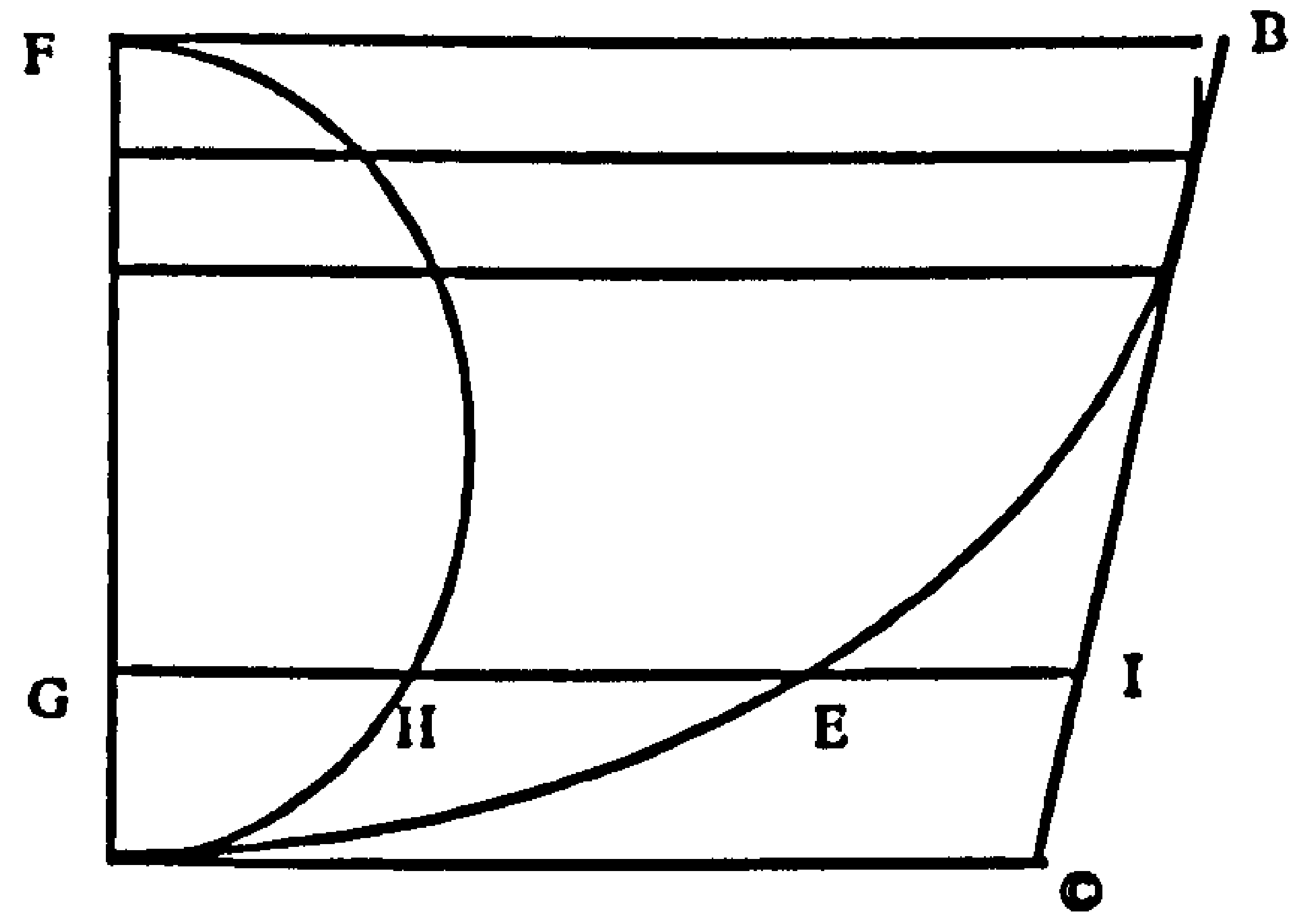


Figure 19 - This geometrical drawing showed the ratios between time of fall through a cycloid and a tangent to it and between the circle and its diameter[218].

By relating a free falling body to that of the cycloid and a tangent to it, he found how a curve, the cycloid, would make a pendulum isochronous. The geometry was simple. He applied Galileo's proposition of free fall to the tangent to a cycloid. He found the ratio of circular motion along the cycloid and the free fall along a tangent to this cycloid; a beautiful and simple geometrical demonstration. Huygens did not deduce the arithmetical formula, but he deduced the cycloid, all the same, and the speed of fall along it as a geometrical ratio. Wallis' letters were important for the demonstrations they had about the cycloid[219]. In December 1659, Huygens claimed to have found the right shape for the cheeks, a cycloid[220].

In the third part of the treatise, he included some theorems on the evolution and dimensions of curved lines, and the quadrature of conics and spheres. Huygens defined curved lines[221] to deduce from simple, basic principles the path the bob of the pendulum would describe once the clock was set in motion[222]. Huygens developed these axioms further in later parts, explaining the properties of the cycloid geometrically[223]. The curve was divided in very small parts and tangents were traced to each point[224] with the corresponding ratios. The geometrical figures become more complicated by studying the curves created from the evolution of simpler ones. He began with a part of a cycloid, which in its revolution would form another part of a cycloid[225] and new curves generating from other curves[226], and their respective ratios[227].

Part four contained the compound pendulum and the centres of oscillation of several geometrical figures[228]. It was difficult to find a curve would make the compound pendulum isochronous. Euler only found this in 1750[229]. This part also contained the universal measure to find the length of any pendulum, which occupied a predominant part in the treatise[230]. In 1646[231], Mersenne had already suggested the centre of oscillation to Descartes and Huygens. For Huygens, Mousnier and Mersenne[232], the centre of oscillation was equivalent to the centre of percussion, which had been defined by Fabry[233] and proved in 1664 for plane surfaces in revolution[234].

Mersenne thought that a rule could be developed to find the centre of percussion, which he later called 'centre of oscillation', of sectors of circles and also define that centre[235]. Christiaan wrote back wanting to know more about the centre of percussion because it was not found in Archimedes' work[236]. Huygens worked on the centre of gravity of solids in 1658 and discussed them in his correspondence[237]. However, it was between 1659 and 1664, that Huygens developed the general rule for the centre of oscillation[238] and that he had worked out the most exact principles to define the compound pendulum, and, he also stated to have found them by experience[239].

Before expanding the general method for determining the centre of oscillation of any geometrical figure, thirteen definitions were given for the simple and compound pendulums used in the treatise[240]. He stated the definition of the isochronous pendulum when the time of each oscillation was the same[241]. He also defined the centre of oscillation of a geometrical figure as the point situated in the central line of the pendulum and at the same distance from the axis of oscillation as that of the simple isochronous pendulum[242]. For the compound pendulum he worked out a hypothesis for the centre of oscillation of a system of weights and their centre of gravity[243] and a series of propositions[244]. He then defined the compound pendulum, with several weights[245]. Other geometrical figures and their propositions were introduced and their ratios found in relation to the square of the divisions made in them[246]. This was followed by geometrical methods to find also the ratios of figures divided in many parts such as a triangle[247], a circle[248], a plane figure[249], a solid figure[250], a prism, a pyramid, a cone, a conic and other figures in general[251].

He developed a general method to find the centre of oscillation of lines, surfaces and solid bodies[252] and described the isochrony of any oscillating figure, a line, a surface or a solid[253]. It was also possible to find the length of a simple pendulum in an oscillating figure with a new proposition. He used the known ratios from the squares of all the parts (*particles*) in which a figure was divided[254]. The distance of the centre of gravity to the centre of oscillation played an important role in the 1664-5 calculations[255]. In 1673 Huygens defined it fully[256], as a straight line equal to the interval between the centre of oscillation and the centre of gravity for the same figure[257]. In an oscillating figure, Huygens found that the distances to the centre of oscillation, or of gravity -being the same- were inversely proportional to the distances of the axes of oscillation to the centre of gravity[258].

Huygens also developed the general formula for the centre of oscillation by looking at many cases of different geometrical figures, such as planes[259], the circle[260], the rectangle[261], the triangle isosceles[262], the parabola[263], the sector of the circle[264], the circle[265], the circumference[266] and the regular polygons[267]. He described how this theory could be used for a plane and a solid figure alike[268]. The general method for the centre of oscillation of solid figures was defined for the pyramid, the cone, the sphere, the cylinder, the conical parabola, the conical hyperbola, the semi-cone[269]. Following this, Huygens deduced the length of a compound pendulum, with the cursor weight[270].

Huygens found the universal measure. The distance from the point of suspension to the centre of oscillation of a simple pendulum was divided in equal parts. If the simple oscillations corresponded to the seconds, each part would give the length of the horary foot, or universal measure[271] so that the lengths of any two pendulums were in a ratio between them like the squares of the times of their oscillations. Therefore, their lengths were in an inverse ratio to the squares of the numbers of oscillations carried out in equal times[272]. The periods of two pendulums were in the same ratio as the times of free fall from equal heights to half their lengths. In turn these half-lengths were in the same ratio as the squares of the times the bodies took to fall freely, and were in ratio to the square of the periods of oscillation[273]. Huygens showed the way to find the space of falling bodies at a certain time of the fall,[274] he excluded the resistance of air.

In the last part, he explained the centrifugal force as well as the circular and conical pendulum clocks (see figure 20). The circular clock was a new construction based in the principle of isochronism already established. Once more, Huygens showed his skills as a mechanical engineer presenting the mechanical design of new inventions and explaining how they worked using the basic mechanism known. It was not a simple clock, although it had the same basic machinery as the pendulum clock and, therefore, it was not used as much. One advantage of this new automaton was that it worked without producing any noise[275].

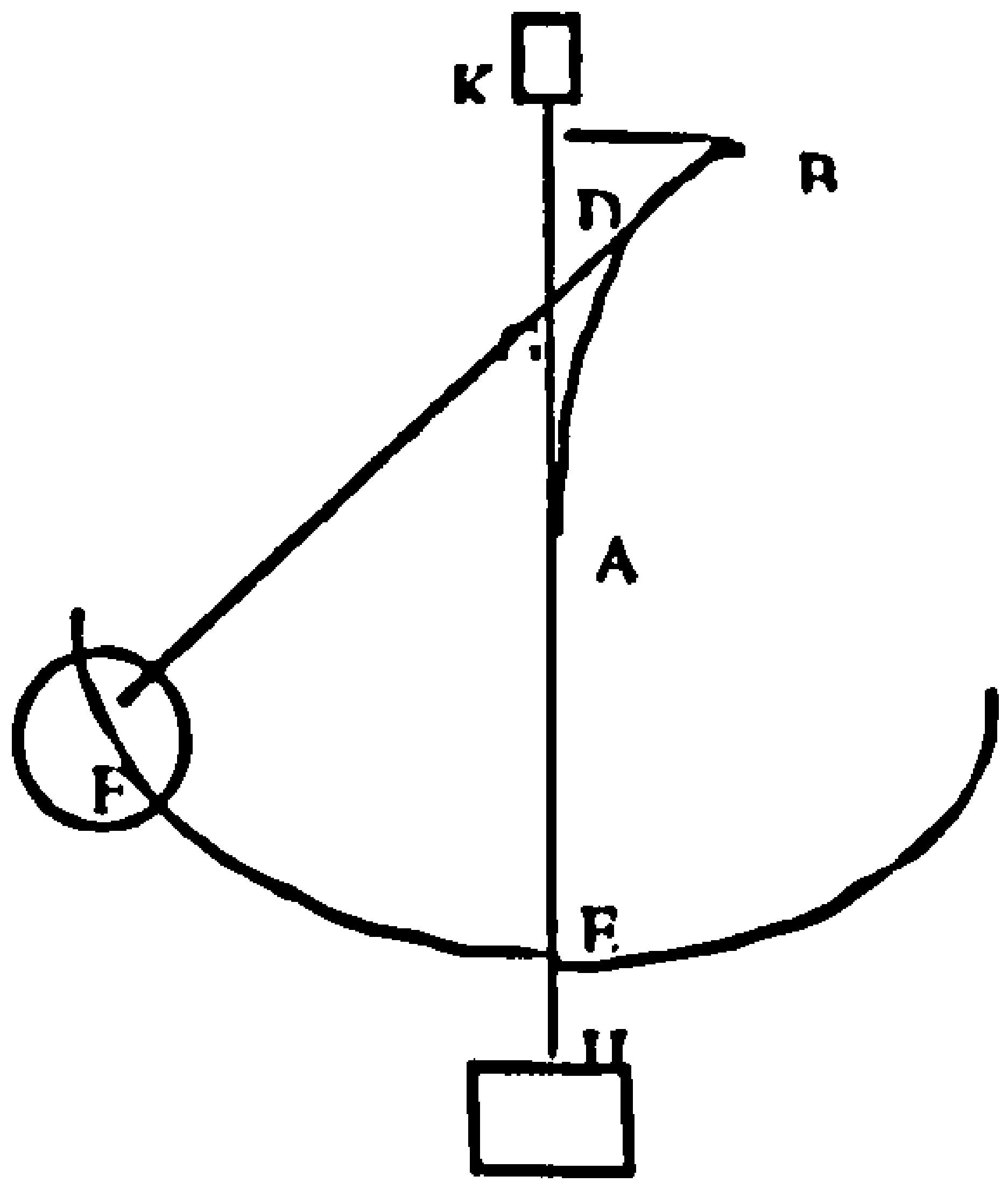


Figure 20 - The circular pendulum clock[276].

This pendulum was composed of a cord BGF and a bob F, a simple pendulum. The long cheek BA was necessary to fill the gap between the double cords at the top of pendulum BGF. This cheek was a paraboloid and its evolution yielded the parabola EF described by the line BAE. The cord BGF described this parabola when oscillating between the BA cheeks. The weight F moved in a circular movement and it was kept in motion by a series of wheels in turn set in motion by weight H. The pinion K made the movement of the axe KH free. The axis DH turned around itself according to the impulse received from pinion K. Huygens claimed to have found by experience that the best material to use in the pinion to help its motion was hard steel and the weight H should be a small plane of surface of *diamant*. Another possibility was to use a chain instead of the cord BGF or gold or another metal, which would keep the length constant[277]. This shows once more the engineer thinking of the available materials to provide a better instrument. As with other automata, Huygens accompanied the circular clock with mathematical propositions and geometry to explain it. These theorems included different ratios such as the direct ratio between a big and a small circumference and their centrifugal forces[278].

He also transferred free fall to the conical pendulum. In this case the circumferences drawn by the pendulum were very small, their period was in ratio with the time of vertical fall from a height equal to double the length of the pendulum. The period was equal to the time of two very small lateral oscillations of the same pendulum[279]. In total Huygens deduced thirteen theorems of the centrifugal force in circular and conical pendulum clocks. He also wrote a total of 16 appendices[280] to the different parts of the Horologium Oscillatorium. They were written at different times, between the original inventions of 1659 and the final writing of the treatise 1694[281], well after its publication. He always followed Archimedean geometry, from simpler propositions to more complicated ones. He used the method of the "*réduction à l'absurde*" at the beginning of some propositions[282].

The Horologium Oscillatorium contained the new mathematical and geometrical deductions Huygens had made over many years. In 1668, Huygens defended his views on whirlpools and of weight/gravity at the Academy. But he did not publish the Discours de la Pesanteur until 1690. However, the correspondence and the presentations made at the Academy proved that his theories on weight/gravity were well known to his contemporaries. He equaled centrifugal force to the weight of a turning body given by the velocity, $V = \sqrt{gr}$. According to Huygens, mg (*the force centrifuge*) was mv^2/r[283]. Huygens got to believe by studying centrifugal force, that this force and gravity balanced each other[284]. One of the main aims of his invention was to use the clock to measure longitude at sea.

3.2. Longitude at Sea

If in 1657 Huygens had obtained the patent for the pendulum clock, it was not until 1660 that he started to work on the longitude, although he had mentioned that the clock could be applied to measure it[285]. The problem was to make a clock that could be carried at sea without disturbing its isochronism. This was only solved when Harrison invented the chronometer in the eighteenth century[286].

3.2.1. Marine Clocks of the 1660s.

An accurate clock to determine longitude[287] was an invention many wanted to develop because it meant fame and also economic success. Society was influencing science directly by giving prizes to design an instrument for specific use. Natural researchers were drawn into designing artifacts to satisfy that demand from society. European Courts had an interest in this invention to gain dominance at sea, also the ships would take less time to reach their destination and would not get lost. For instance, the French clockmaker Martinet[288] was interested in applying the clock to find longitude. In 1662 he was experimenting with a small pendulum to be used for longitudes[289]. From 1662 onwards Huygens worked on marine clocks (see figure 21).

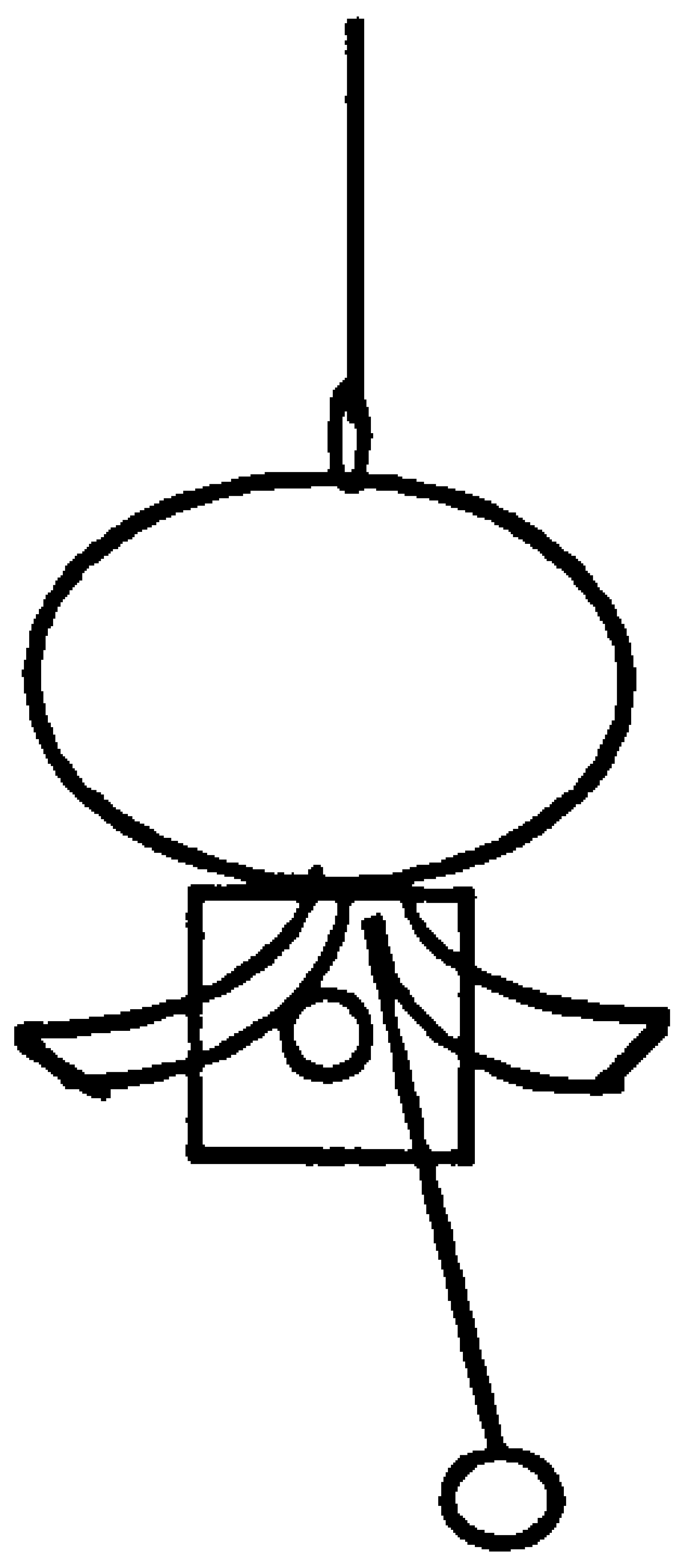


Figure 21 - Huygens' marine clock with large receiver[290].

Some samples of marine clocks made in The Hague were sent to France and England[291]. It was the general belief that Dutch clocks were good and the best in Europe until the early 1660s. Dutch clocks influenced the French in the 50s but later, in the 60s it was the other way round. Maybe because after 1666 Huygens had most of his clocks made in

France and had introduced improvements. Also the 21-year patent obtained with his first pendulum clock and the subsequent disputes with Dutch clockmakers may have deterred other instrument makers from trying to obtain a patent, therefore, slowing down the innovative process in Dutch clockmaking.

In February 1662, Huygens made public a table of results of two years calculations of the equation of time[292]. The inequality over any amount of days was obtained by simply subtracting the results of that table[293]. He also explained the way to set the right length for the pendulum[294]. At this time, several long pendulum clocks were commissioned. Moray asked, in 1661, for a three feet long pendulum[295], and W.Brouncker, president of the Royal Society, received another clock made by Severyn Oosterwijck[296], who made clocks for Huygens in The Hague and for contemporaries in France[297]. Huygens and Oosterwijck quoted the price for the clocks and they were built once agreed. Pascal was another clockmaker from The Hague who worked a lot with Huygens[298]. Bruce, count of Kincardine, had some clocks made for Huygens and sent them to him via Moray. He knew the mechanics of the clock and also worked with Huygens to perfect the marine pendulum clocks.

Three new models of the marine clocks included: the triangular clocks, of 1662 and 63 (see figure 25); the clocks with a remontoir wound up with a system of weights and chains (*remointoir à poids moteurs*) of 1664 and those with a winding mechanism of chains "*horloges a remontoir*" of 1665. It is not known if some of the designs of the triangular clocks were built, between 1662 and 1663[299]. In 1667 and 1669 he made other models: circular and conical pendulum clocks[300]. He obtained a patent for the chain/weights clocks, which are a further proof of the engineer, designing new variations to the pendulum clock. The different suspensions used included one of long cords -5 feet- at the end of which there was a small platform with four pendulum clocks, one in each corner of the platform. They also included the design of cardan rings (*anneaux de Cardan*) to support the pendulum (see figure 22)[301].

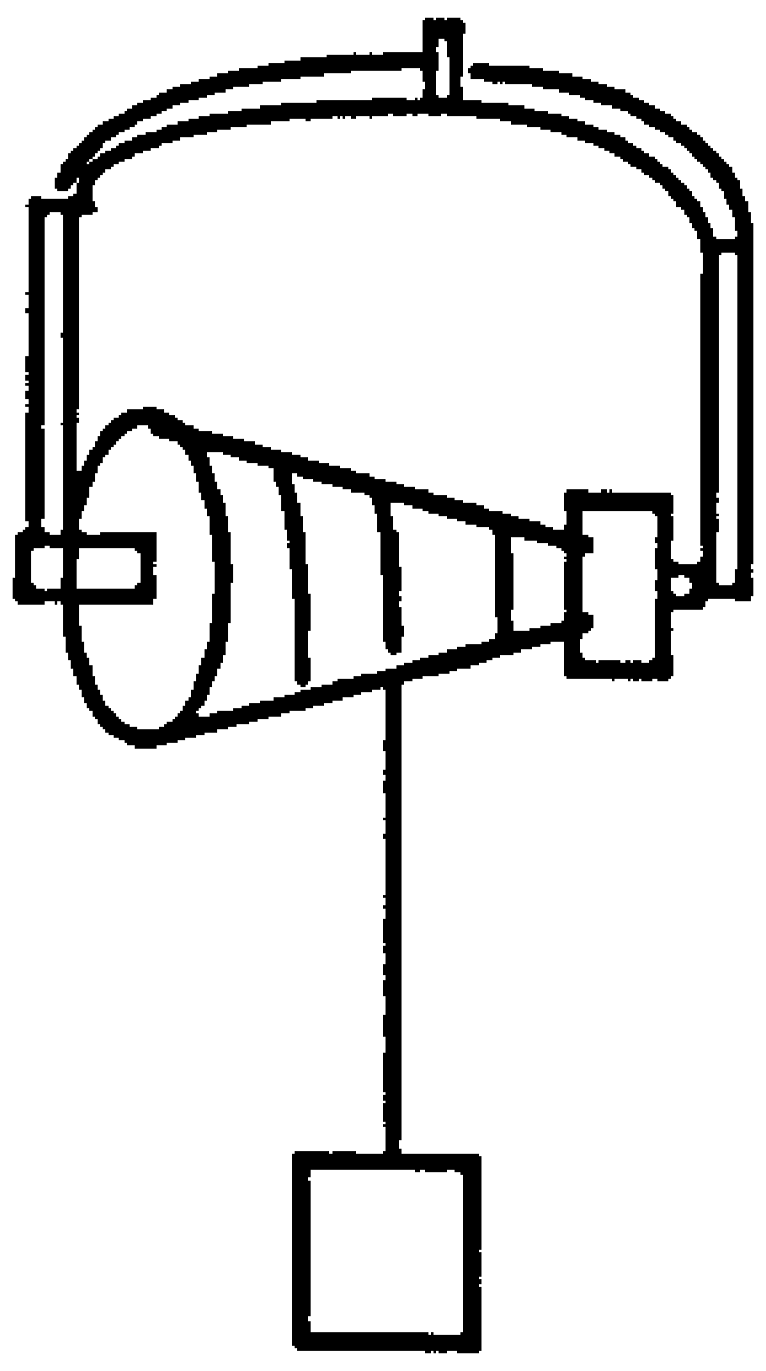


Figure 22 - The cardan rings (*anneaux Cardan*) designed for the suspension of a marine clock [302].

Oosterwijck, following Huygens' instructions[303], built marine clocks for Bruce[304]. Huygens suggested a small change in them by making a metallic circle through which the cord of the pendulum passed[305]. The objective was the same, to improve these clocks and replicate them. They were powered by a spring and had a cursor weight. Bruce thought of suspending the pendulum clock from a big sphere of steel, placed inside a cylinder of leather[306]. Other drawings do not seem to have been made for marine clocks, but their function is not clear. One is an axis with a vertical cardan ring supported vertically by a box and another arm[307]. Another drawing shows many geared wheels with the number of teeth and a time written by their side[308]. Huygens could have been drawing what he thought the different wheels would achieve, without having the intention of using them in a clock.

In 1664 Oosterwijck made more marine clocks[309] for Huygens who obtained a patent for a marine clock with a long pendulum in December in Holland. Instead of a balance, this clock had a rod of wire or a "thin narrow plate with a weight at the lower end, called pendulum A, and, at the upper end, an Arm with two Catches or Rules to move it and cheeks to regulate its motion". It was fitted with "Balls and sockets to hang by for going at sea"[310]. This patent did not allow anybody in Europe to make clocks for use at sea as Huygens said to Moray[311]. It was the "*horloge a remontoir*". The winding mechanism of these clocks was of chains as his designs showed clearly[312]. He also obtained privileges for the same clock in England; he obtained a 'patent roll 3072' to make these clocks for 14 years[313]. It took Huygens a much longer time to obtain the patent in England[314] than in The Netherlands. Bruce had adjusted the pendulum in the clock with a double clutch to resist the movement of the ship better[315]. He could understand Bruce's name in the privilege but not the Royal Society's[316]. Then Huygens decided that it could be easier if Bruce had the privilege in his name[317]. However, it still took some time until all the parties were satisfied. Bruce was not satisfied with the conditions Huygens had suggested[318] and, finally, Moray arranged it so that Huygens would have 25% of the profits, Bruce another 25% and the Royal Society 50%[319]. The war between The Netherlands and England slowed communications between these countries and Huygens mentioned it in his letters[320]. In France, that year, Louis XIV granted him a privilege for the same marine clock, his father Constantijn asked for the privilege to the King; it was granted on March 1665[321].

During 1664, Huygens made a long list of improvements for the marine clock. It contained a series of instructions for the clockmakers[322], showing once more the direct relationship he kept with them and how he knew they would understand his drawings. Between 1664 and 1665, Oosterwijck made marine clocks enclosed in a box with a cursor lead weight[323]. One of the experiments that Huygens carried out to observe how accurate these clocks were was setting them up both together hanging from a plane placed over the back of two chairs (see figure 23)[324].

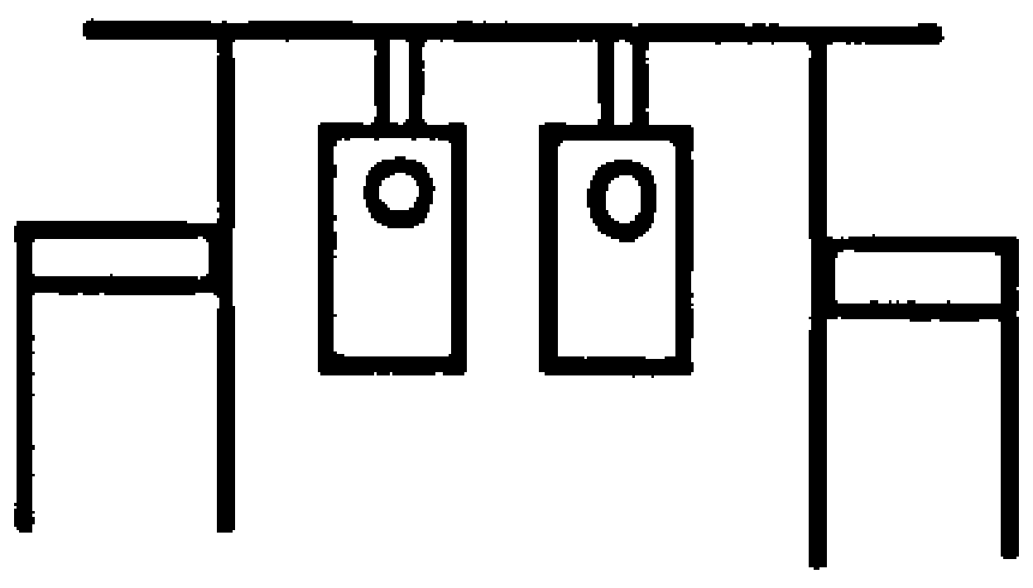


Figure 23 - Experiment to check the accuracy of two marine clocks set at the same time[325].

Not knowing that this was not the way to test how precise the clocks were because due to their proximity they would give the same time eventually, he registered the same time in both of them as a way to prove their accuracy. However, and to prove his skills as an experimenter, it is interesting to note that by comparing these clocks Huygens realized three things. First of all, he thought he was able to eliminate some errors of precision he had not foreseen[326]. Secondly, he saw that temperature affected the clocks differently in the experiments of April 1664. However, from August to November, and after adding a second "*remontoir*", the clock worked accurately. Finally, he knew the need for accuracy and thought he had designed experiments to calibrate them[327] by comparing two identical clocks[328].

In 1665 he observed that the trains of the clocks moved in sympathetic motion "*sympathia*". Huygens noticed how the sympathetic motion appeared as he hung the clocks closer "*en approchant... les pendules se sont remises dans la meme train*" [329]. There was a short debate on the subject. Moray suggested that maybe it was due to a magnetic cause, or air, or some other unknown factor[330]. Huygens explained that it was not due to the air but to a small "*branslement*". Furthermore, the clocks had to arrive at this sympathy and keep it afterwards "*je demonstre que necessairement les pendules doivent arriver bientost a la consonance et ne s'en departir apres*"[331]. This statement convinced Moray because according to Huygens, who was wrong, the clocks seemed to rectify each other giving more "justesse"[332]. Chapelain still questioned all this and argued that air must be the cause[333]. Huygens attributed the outcome to the distance kept between the clocks and Chapelain insisted that more experiments were required to prove this[334]. For Huygens sympathetic motion was a proof of the clocks' accuracy because their motion was then kept constant[335]. In one of their assemblies the Royal Society concluded that Huygens was right[336]. This issue had been intensively debated by letter during the month of March, was settled by April when the scientific community decided to agree with Huygens. It is a pity that the debate did not continue. Maybe Huygens would have then tried other experiments to calibrate clocks instead of hanging them so close together. This quick and non-argumentative way of settling new phenomena shows the great authority his colleagues gave Huygens in the seventeenth century.

As the engineer, he continued improving the marine clocks, introducing ingenious inventions. One of these models already discussed; the triangular pendulum clocks were not tried until 1686[337]. Their pendulum was nine French inches long and the bob half a pound in weight[338]. The variety of marine clocks is also impressive and of the many models he designed maybe some were never built.

3.2.2. The pendulum clock adapted for trips at sea. The trials of the marine clocks at sea

Soon after a marine clock was made, trials at sea were necessary to see how the pendulum would respond to those trips. The clock had to be kept working regularly and accurately at sea in order to measure longitude. The first trip of 1663 did not yield the expected results. The sea was too rough for the pendulum to be able to swing at constant, regular intervals, and Huygens tried various experiments and new designs to make a clock that would measure longitude at sea. He communicated this to the States General[339] who showed an interest in this idea[340]. Several contemporaries, including Hooke, were also experimenting trying to find a good regulator for use at sea[341].

Huygens wrote a treatise on how to measure longitude at sea in 1665[342]. The treatise included measuring tables obtained on the voyages. The first voyage was to Portugal, from April to September 1663. The captain of the ship was Robert Holmes who reported regularly on the clocks used[343]. Two clocks were tried. The first clock was from Huygens, clock A, from The Hague, the second, clock B, was from Bruce[344] who adapted the pendulum to the marine clock in the same way as Huygens. The voyage was considered more or less satisfactory. Both clocks had yielded similar results when measuring longitude[345]. Moray commented that the clock from The Hague was better[346] than the one from England. The objective was to see if the longitude at sea between two places was the same as that obtained in previous calculations. In 1664 Huygens wrote a treatise of instructions for the pilots to use the clocks at sea[347]. They were translated into French and English[348], but they have not come down to us[349]. Huygens obtained a patent from the States General for these clocks in December 1664. The instructions were published in 1665 under the title: "Brief Instruction on how to use the clocks to find the Longitude in the East and in the West"[350]. These instructions are a further proof of Huygens the engineer. A new system of instruments accompanied by instructions or their use had begun. Nowadays, this is a standard procedure. Holmes continued on a second voyage with the same clocks to Guinea and Jamaica[351]. He returned to London in January 1665[352]. Huygens was kept informed on the second voyage too[353]. It must have been the success of these voyages that gave Huygens the confidence to say that the clocks were very useful and should be sold in the open market[354].

After publishing the instructions for the marine clocks, in March 1665, Huygens held conferences not only with pilots and seamen[355] and commented on how difficult it was to persuade seamen to adopt something new even if the utility was evident[356]. The instructions included a way to adjust the clocks and, therefore, calibrate them by using other clocks on land. Once aboard the ship, a clock should be checked for accuracy with another clock and set with the time of the day given by the sun. The table of the equation of time found in the instructions, also given in the Horologium (1658), should be used to correct the error of the day[357] and adjust the clock further with the cursor weight. If the clock was fast, the cursor could be lowered a bit to make it go slower. But if the clock was slow, the sliding weight could be raised[358]. All the clocks should be observed for accuracy[359]. It was important to calculate the hour at sea with precision because an error of one minute in the clock would cause an error of a quarter of a degree in the longitude[360].

In December 1667, Huygens wrote to his brother Lodewijk about new clocks without "*la chainette en dedans*"[361], similar to ordinary pendulum clocks. One of these had a rotating pendulum. During this time Huygens designed clocks of "*verge à palettes*", some with a vertical geared escapement[362] and horizontal in others[363]. Another conical pendulum was built in 1668. In order to stop the clocks from moving once at sea, he devised another experiment. He hung two marine clocks from a beam (figure 24)[364], or from a cardan ring. They were going at the same time. Following the outcome of the experiment of 1665, Huygens still believed that it was better to have two clocks closed together in order to calibrate them.

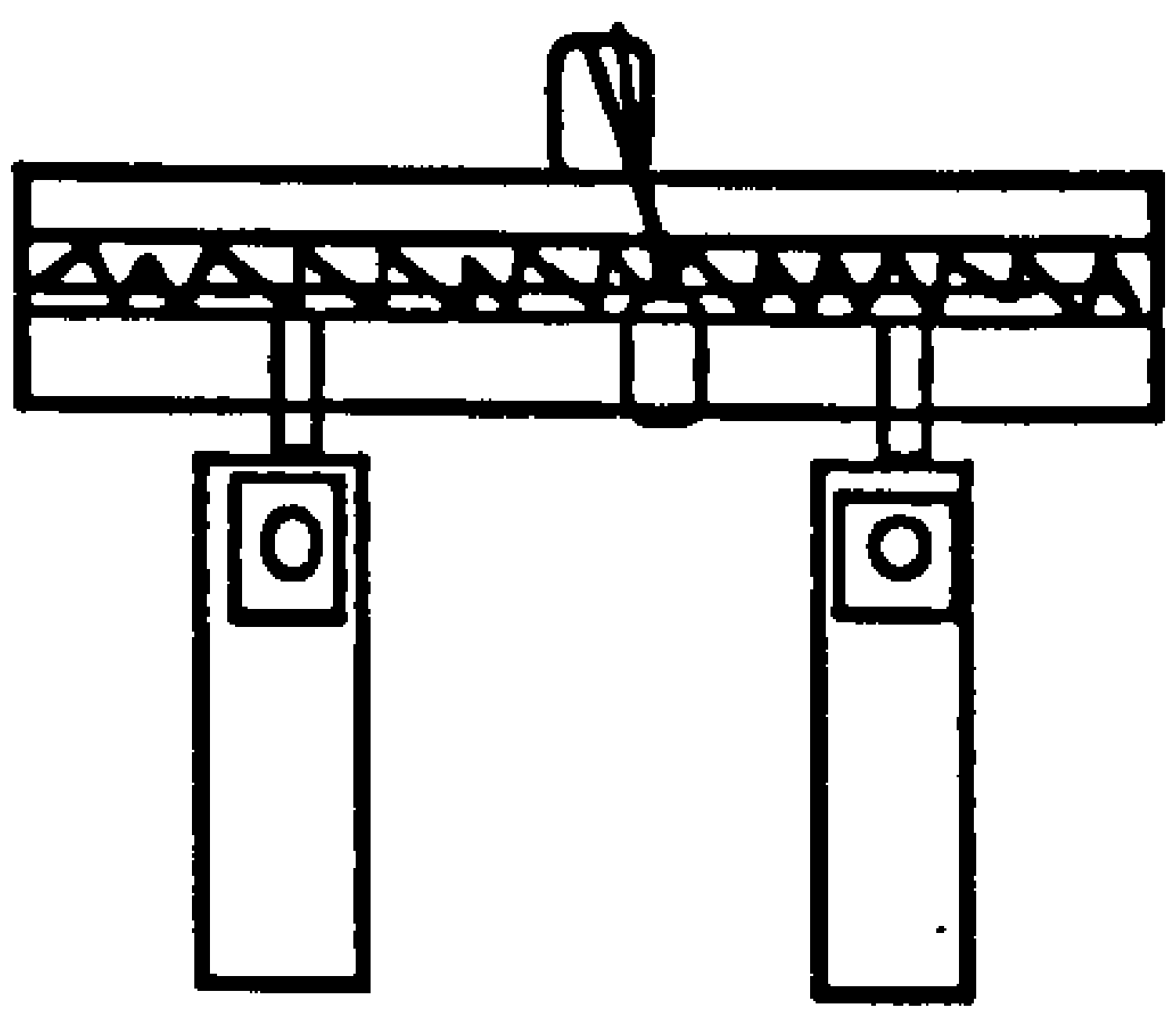


Figure 24 - Marine clocks of 1668 hanging from a beam and with the pendulum shut inside a box[365].

Huygens continued his search for the best design and support for the marine clocks, so that they would be affected as little as possible by the movement of the ship at sea. These two clocks (figure 24) had to be exactly of the same construction and were kept going always at the same time. The sun was used as a reference to start them.

The voyages did not work well. One problem may have been that the clocks were not well looked after. Also the records may not have been carefully done. These may have seemed accurate enough to a seaman, but something may have escaped him that the experimenter would have seen. It is also difficult to know how well they followed the instructions given by Huygens on how to set them at the same time, and how often they corrected their accuracy as the lists of corrections made by Huygens in August 1668 for the different marine clocks show[366]. He did the same that year, after the expedition to Lisbon of the Duke of Beaufort, and maybe influenced by the remarks made by the duke on the clocks[367]. Once improved, the marine clock of 1669 was sent to sea and observed in a second expedition to the Mediterranean[368]. He designed more supports for the pendulum with bigger bobs between 1668 and 1670[369]. There was another expedition to Cayenne but the clocks were not used. He also drew some marine clocks suspended from a cardan ring[370]. Huygens pointed out that the marine clocks with a pendulum were the first of their kind, the most precise being the "*chain à remontoire*" clocks[371] and from 1665 onwards, Oosterwijck had permission to build them. Whereas, Thuret built the clocks with "*à remontoire à poids moteurs*"[372]. John Fromanteel made marine clocks for Moray[373] and also for Bruce and Huygens. These were known as some of the best clockmakers of the time.

In 1671 and 1672, Huygens designed marine clocks with "*à ressort moteur*" and a triangular pendulum, suspended from a cardan ring[374]. However, these clocks had still not been tried in 1673. It is not known if some of the designs Huygens made of clocks at this time were ever tried.

They may have only been designs[375], but they show the importance in mechanical engineering of changing parts of a machine from their mechanical designs. Huygens also thought of suspending the bob of the marine clock from a triangular pendulum[376]. The triangular pendulum was set in a box under the clock, which in turn was fixed to a frame to make it more stable[377]. The design found in the Horologium Oscillatorium was that of a marine clock[378]. The pendulum was suspended as it is shown in figure 25.

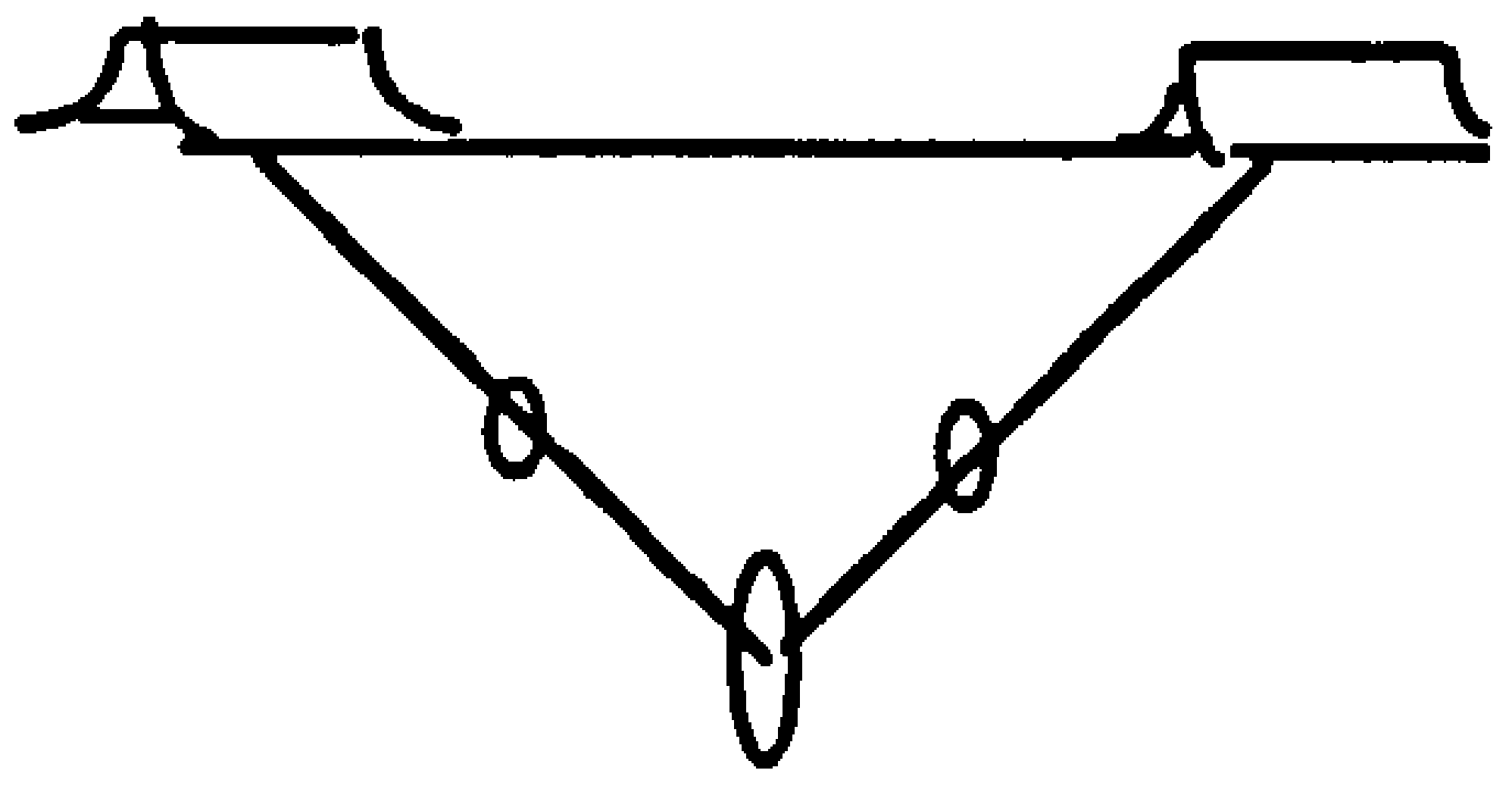


Figure 25- The triangular pendulum of a marine clock of 1671, or 1672[379].

The movement of the pendulum was affected by the changes of temperatures and by the movement once at sea[380]. Huygens wanted to use the pendulum clock of 1673 at sea and tried it in different voyages, to measure longitude in a more precise and easier way than it had been done traditionally. However, the voyages gave unspecific results and no final conclusions could be drawn from them, even when the English, the French and the Dutch[381] had also carried them out. Huygens said that this could be attributed to negligence of those in charge of the clocks during the voyages. It was when a good astronomer was put in charge of them in the expedition to the island of Crete that results seemed to improve a little. The longitudes found coincided with those already known in the same places. It should be noted that the Mediterranean sea is much calmer than the oceans and, therefore, the clocks would keep more regular swings, maybe this was one of the factors of such an improvement.

Another kind of clock, the astronomical one, was being made and sold in 1672[382]. Huygens obtained a privilege in France only for the marine ones. Thuret made them and sold them from 1666 onwards who must have made the pendulum clocks found in the palace of Louis because he was *Horologer ordinaire du Roy*[383]. In the dedication of the Horologium Oscillatorium to Louis XIV[384], Huygens said that this type of clock had been made from 1667 until he realized that he had to find a way to compensate the expansion suffered by the metals used. But he did not seem to be convinced of this until 1690[385]. The astronomical clock of the Leyden observatory could be from 1673, or a bit earlier[386]. The clock worked well and lost only 1 second per day. It worked better if it was suspended from a man's height and the amplitude of the swing was of 12° [387].

3.3. Other clocks after 1673. Watches with a Spiral Spring (1675). Marine Balanciers and the Portable Clock

Huygens won great admiration among his European contemporaries, with his Horologium Oscillatorium[388]. His study of the mechanics of the clock after 1673 followed a well-established method from the Horologium of 1658. And although there were no more editions of this treatise, Huygens continued improving some of its propositions up to 1694[389]. Roberval, however, objected to some of Huygens' demonstrations on the motion of the pendulum[390], mainly on the centre of oscillation. Huygens responded to all of them[391]. After Roberval's death in 1675, Catelan continued the objections against Huygens' work of 1673[392]. At times it seems more like a personal attack, Huygens showed that Catelan had misunderstood him; however, Catelan still kept to his conclusions[393]. The discussion continued for some years. In 1684, Jacques Bernoulli also intervened in the debate[394] and it was still mentioned in 1690[395]. This kind of direct attack may have damaged Huygens as an outstanding scholar in the field of science to the eyes of the bureaucrats and maybe was another factor of why he was not called back to France after Colbert's death (see chapter 5). After all Catelan was French and catholic. In the late seventeenth century very few foreign scholars appear in the Mémoires and Histoire of the Academy, maybe because they were more expensive than their French counterparts and the Treasury had lost a lot of funds with the Dutch war.

In 1674 Huygens worked on designs of new-geared wheels for the clock. He followed Roëmer's advice to make epicycloids[396] and explained them, once more, with mathematical ratios. Between 1673 and 1675, he worked on harmonic vibrations and compared them to cycloidal oscillations. From this he concluded that inherent force existed in bodies and different things such as weight/gravity; elasticity and others caused it[397]. Although only outlined, Huygens was the first natural philosopher to develop a theory of harmonic vibrations. Newton did so later in his Principia of 1687[398]. Leibniz attributed to Huygens the discovery of the law of *ressorts* (springs)[399]. Huygens wrote back in March 1691 explaining that experience had showed that there was isochronism of vibrations of the *ressort* if it expanded in the same proportion as the force impressed upon it[400].

Huygens defined the difference between the force exerted on a body and *incitation*, which he defined as the force inherent in bodies and was caused by either the action of weight/gravity, elasticity, or other cause. The idea of force and power of a system of bodies, was taking shape in Huygens' mind. Although only outlined, the law of the isochrony of vibrations, as well as the principle of *incitation* of 1674-5, show that Huygens continued working in mechanics to explain the concept of force and the perceived concept of power, essential for any machine, or engine to work. Huygens did not require a philosophical discourse to deduce any of these principles, or to convince others of their existence as natural philosophers did. He was outlining the beginnings of modern mechanics. A good example is given in the piece of 1674-5 (see figure 26). Huygens defined perfect *incitation* as caused by a principle of infinite velocity, which restitutes the *ressort*. It was the spring of the air that was fastest, it required a direct mechanical explanation.

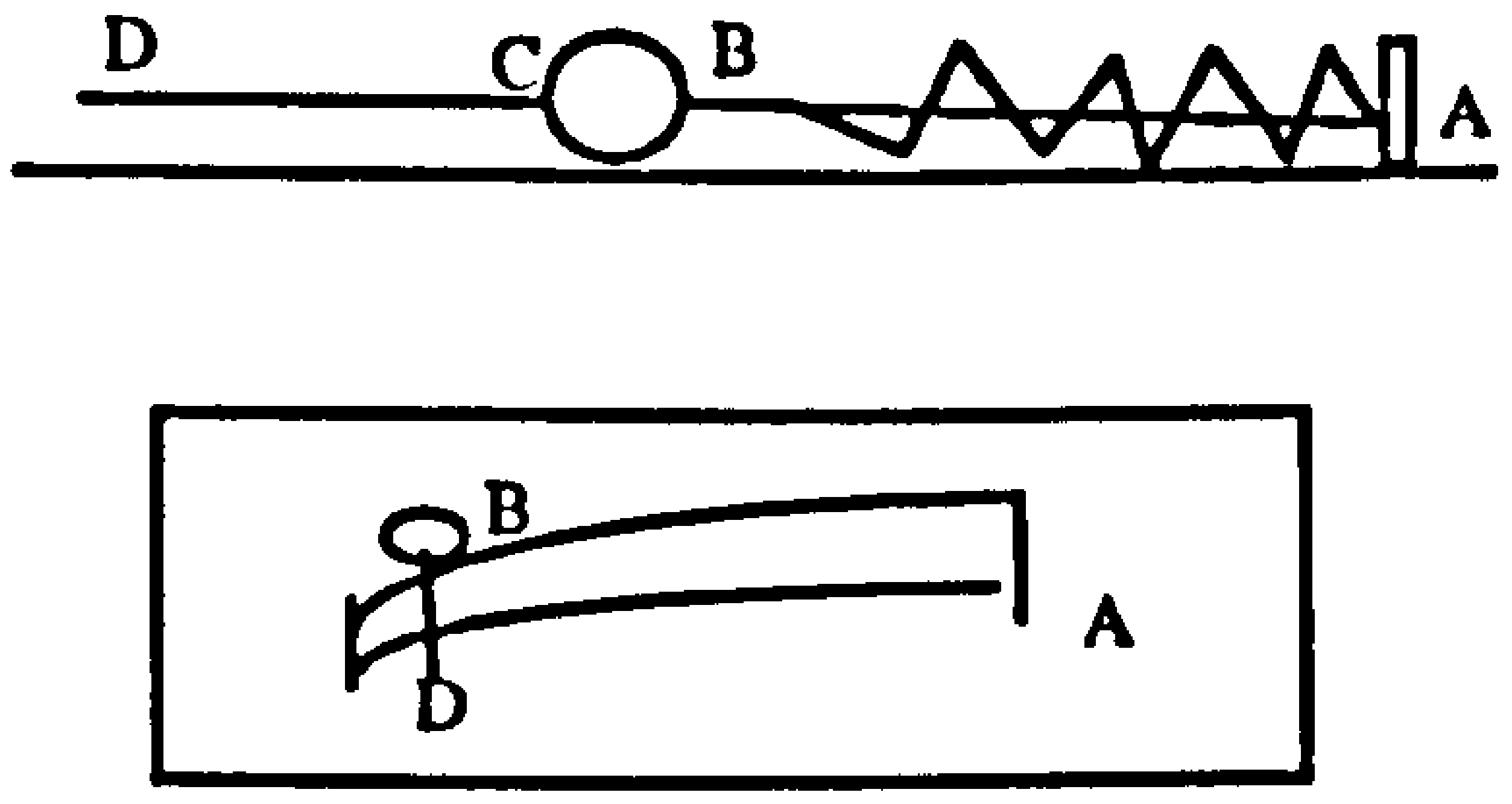


Figure 26 - A spring could impress motion upon a body.

With this experiment Huygens proved that the *incitation* of a body once set in motion, or accelerated, by the action of a spring, could be measured, at each point, by the force which had to be applied to stop it from moving in the direction of the force impressed upon it by the spring (see figure 26)[401]. The spring AB was attached to A, and moved the body C. The *incitation*, or impressed force, at B was equal to the force necessary to maintain it in the state of rest[402]. This impressed force was the same, either if the body was set in motion, or if it was already moving. Although in this system Huygens considered the weight of the spring negligible, in an impressed/inherent force, both, the body and the spring were essential factors[403].

Huygens concluded that impressed/inherited forces in/of bodies from different causes could be compared and found that they were the same. It could be compared to the spring of the weight/gravity (*pesanteur ressort*) in the attraction of the magnet or any other cause. He called uniform impressed/inherent force (*incitation uniforme*), or perfect impressed/inherent force (*incitation parfaite*), to that which remained constantly equal, similar to that of the weight/gravity upon a body descending in free fall or along an inclined plane[404]. If it increased constantly, it should be called increasing impressed/inherent force (*incitation croissante*), but if it decreased regularly, it would be called a decreasing impressed/inherent force (*incitation decroissante*). From all this, a hypothesis was deduced. Two bodies following parallel lines with the impressed/inherent forces equal between them, at each equally advanced point in both lines, whatever the origin of the impressed/inhereted force, crossed both lines in equal times[405].

Huygens realized over the years that in order to keep an instrument in motion the machinery of an automaton was not enough. Influenced by Stevin's work, Huygens discussed a *force vive*[406]. He looked for a mechanical design that would maintain a machine in constant motion by using the force/power drawn from a system of weights. Stevin, in 1586, designed a system of two weights linked by chains and moving around two inclined planes to determine the equilibrium between them. In 1676, Huygens drew Stevin's demonstration and believed that it was a good way to prove the non-existence of constant motion (see figure 27 in footnote)[407].

Stevin's work on engineering remained within the old tradition of fortifications and draining areas of land. In the late 16th century, Stevin still remained in that tradition and was known for his water works. Stevin issued several patents on drainage mills he had invented to pump water and drain areas of land. He explained how these inventions worked based on the movement of the designed system of wheels and cords with the help of some basic geometry[408]. Stevin's geometry was not what influenced Huygens since he developed his own. It was Stevin's composition of forces in a system that Huygens found of interest and value[409].

In the Middle Ages systems of forces were studied with geometrical figures, such as a triangle and a square as the centre of a system. Roger Bacon in the 13th century discussed them in his Opus Majus[410]. Stevin developed the medieval tradition of general statics much further and applied it to draining mechanisms.

The study of the conservation of forces was also important in Huygens' mechanics. It was necessary to develop the mechanics of motion further. Huygens did not have an engine to maintain the motion of an instrument regularly and continuously. Very simple dynamics of weights kept the clocks, so far designed, going. But he had to get a better basis by using a power source to produce a constant motion. He began to realize this in 1693 and defined the axiom of perpetual motion, using force in the sense of power.

In 1693, Huygens formulated the theory of the conservation of forces[411]. *Vis*, force, was now defined as *potentia*, power and not force as defined three years earlier. In 1690, Huygens had defined the law of conservation of forces as one by which the bodies kept a force, which could raise the centre of gravity, common to those bodies[412]. Huygens thought that a mechanical way to obtain a permanent power was with the use of a magnet. He said this to Leibniz who had written to know if a prize could be suggested to the States General for the person who would discover constant motion[413]. In 1666 he thought he could use magnetism in clocks[414]. He also knew that constant motion could not be found at least as far he had tried. In 1675 he worked with hydraulic pistons and springs. As Duhem[415] says the search for constant motion is one where we find two different utopias, the search for a 'constant motor' and 'perpetual motion'. I believe Huygens was looking for both.

As the engineer, Huygens was looking for a source of power to keep the machinery of the clock going. There were no steam engines yet, but Huygens had the vision of a way of using some source of power to keep a machine in motion. This is a further proof of his engineering skills and intuition for the creation of new mechanics, but which he could not develop with the physics of the time.

Huygens found that, apart from the cycloidal cheeks, other systems of impressed/inherent force (*d'incitation*) could also be isochronous. Huygens developed the law of harmonic vibrations, or the principle of springs as Leibniz put it, in the early 70s. With the theory of how springs could be applied to make a watch isochronous, Huygens was the first to apply the *ressort en spirale* -spiral spring- to small watches in

1675[416], rather than the balance spring[417], and he found the theory to explain the system. In all cases the *incitation* was proportional to the oscillation gap and the period was also independent of the amplitude of arc[418].

Other experimenters were also looking for different forms of maintaining isochrony to keep a clock working with regular oscillations, without the use of the pendulum. In 1678 Hooke developed the law of elastic vibrations. The cycloidal pendulum was not necessary to maintain isochrony[419]. The principles and laws deduced for the springs were not as easy as those found for the cycloid. In 1675 France, it was known that Pardies had applied a spring to the balance wheel of watches[420]. Leibniz gave Huygens priority to Hooke's annoyance[421]. This year, Huygens said that since 1660 he had tried to apply the spring he had seen in French watches. Thuret and the Duc de Roanais/Roanez had suggested the use of the spring instead of a pendulum[422]. He wanted to apply it to regulate the isochrony of the clock, and not only to keep the clock going as it had been used so far. With the theory behind the principle of harmonic vibrations, he was able to apply the spring to the watch as a regulator of precision and isochronism. Huygens' spring was a spiral (*ressort à spiral*), whereas Hooke's was helical (*ressort helicoidaux*), and Hautefeuille's was a *ressort à droit*[423]. Huygens sent an anagram of it to Oldenburg in January 1675[424]. Huygens maintained discussions over priority of the spiral spring with Hooke, Hautefeuille and Thuret with whom he was reconciliated later. It was believed that Huygens' spiral spring to modify the vibration of the balancier in watches[425] was better than Hautefeuille's. Thuret built these watches[426]. In trying to explain this episode, Baillie has taken a diplomatic approach. He claims that Hooke had the "conception" first, but Huygens published and had it made[427]. The dispute over priority with Hooke has been fully described by Iliffe[428].

Unlike for previous clocks, Huygens did not build the watch with spiral spring. It was Thuret who made these watches, following Huygens' drawings and explanations[429]. Thuret did not keep the secret of this watch[430]. On the contrary, he claimed the invention for himself and, once more, Huygens had to maintain long discussions with a clockmaker who wanted to claim the merit of his invention. In The Hague, Oosterwyck made watches with (*à ressort droit*)[431]. But the watches with *ressort à spiral* took over. In January 1675, Huygens wrote on the balance wheel of a watch regulated by a spring[432]. These watches were found in European Courts. The Stadholder William III had one made in July[433], also Louis in August[434] and the Duke of York owned one in September, the same year[435].

Huygens obtained several privileges from France and The Netherlands in 1675. In February the same year he obtained another one in France for portable clocks for use at land and sea[436]. In The Netherlands two privileges were obtained, one for a marine clock invented but not built[437] and another one for pocket watches[438] (see patents section below).

The spiral spring could be applied to watches in different ways. First of all, it could be attached directly to the axis of the balance wheel[439]. The second was applied over the axis of the verge with palettes. A wheel was then attached to the latter and to the spiral spring, so that the balance wheel produced wide oscillations, the *échappement à pirouette*. Huygens published the third way in 1675 with a figure. He used this ressort spiral in the watch of 1675 (see figure 28)[440]. The fourth way of applying the *ressort à spiral* was to use two balance wheels, where the pinions were in mesh. Huygens thought it would be better to use two springs, one for each wheel, rather than one[441]. He drew what he meant by this in a figure[442], as he had done with any new invention or with the parts he wanted to improve. He used the springs as motors.

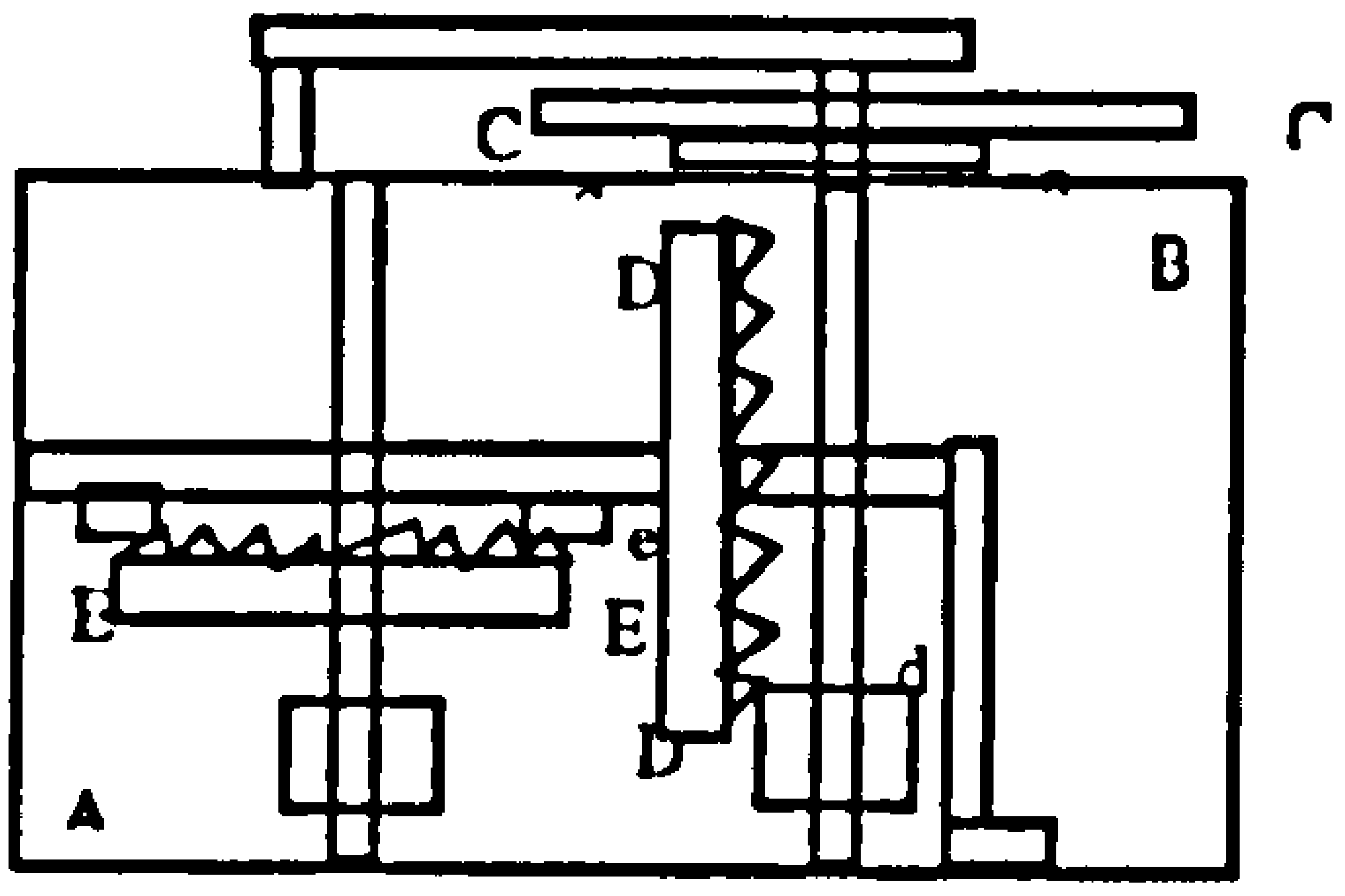


Figure 28 - Watch with *ressort à spiral* of 1675.

In the figure, *CC* is the balance wheel, *aa* is the *ressort à spirale* and *d* is a pignion that makes the balance wheel give wide oscillations. Maybe Thuret made a clock like this[443]. Huygens said that Hooke's clock was similar, with the same kind of balance wheel, hardly a change[444].

Already in 1666, Huygens had noticed that temperature affected the springs. Thiry claims that the first to say that the inequality of oscillations depended upon temperature was the Belgian Wendelen. But he does not prove it[445]. In 1675, Hooke[446] and Justel[447] also noted this influence. Huygens described it more directly to Justel[448]. In order to prove this, he carried out several experiments. However, in that year and in 1683, Huygens thought that the clocks worked well and insisted on their public utility to Colbert[449].

After 1675, other clocks included the triangular clock[450], which Huygens believed would be more stable at sea and would correct the movement of the clock. When Huygens drew the anchor escapement of 1675, he also wrote the name of Roëmer and Leibniz in the drawing[451]. Roëmer and Leibniz were in France in the early 70s. Leibniz went to England in 1673 and knew about the anchor escapement that he must have described to Roëmer and also to Huygens[452]. However, it is not known when it was invented[453]. In 1683 Huygens designed a *remonte* to make a clock more precise, not allowing the escapement to stop at any moment of the clocks with *ressort*, therefore, maintaining their power better at sea[454].

In 1680 Van Ceulen made planetaries and marine clocks for Huygens who thought that *ressorts à spiral* could be applied to them. Huygens drew several double balance wheels geared by two pinions and one escapement wheel[455]. In 1682, Huygens suggested a trial for the new clocks[456]. In July, August and September 1683, Huygens mentioned two clocks built by Van Ceulen[457]. In December, Huygens brought Van Ceulen a drawing for a cylinder built pendulum in order to improve the previous two clocks that were made for the company of *Indes Orientales*.

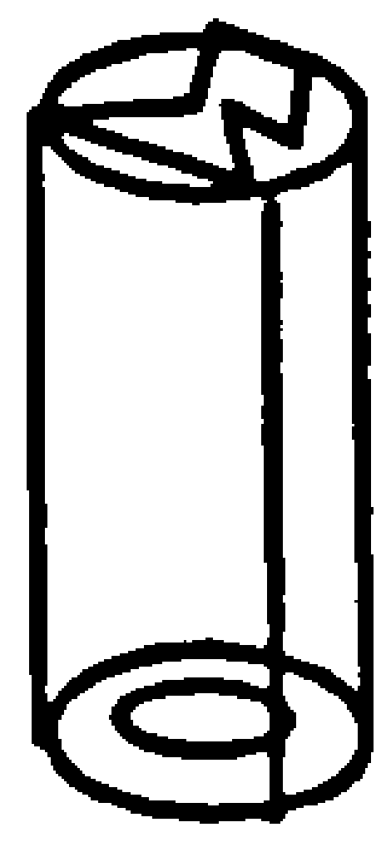


Figure 29 - Cylinder built for the pendulum of 1683[458].

In 1659 Huygens had already thought of a piston for use in a conical pendulum[459]. In 1683, or 84, he had designed the perfect marine balance, *balancier marine parfait,* (a balance wheel) and applied it in 1693. (see figure 30). It is obvious that he was looking for a constant source of power to keep the clock going. This was also the aim when he studied the impressed/inherent force with the springs from 1673 until 1675.

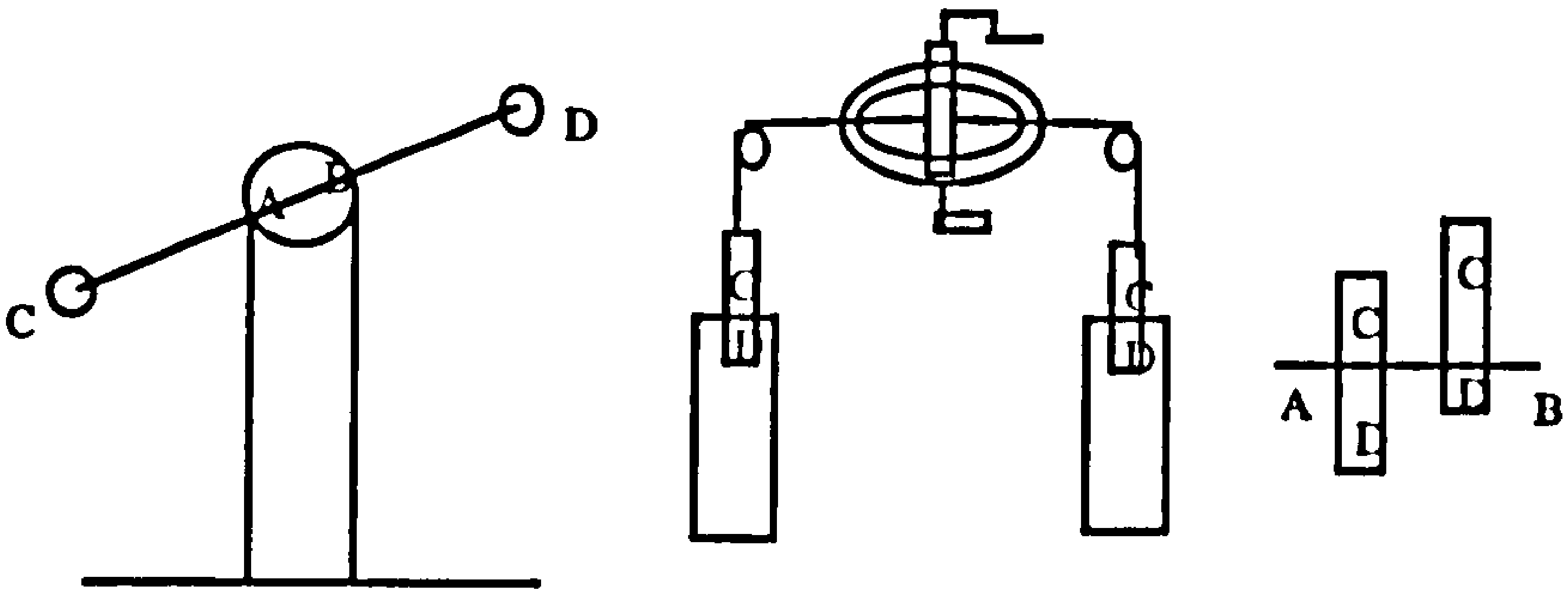


Figure 30 - The perfect marine balance of 1683-4 with the use of pistons[460].

The pistons were filled with mercury. The cylinders C and D were placed in an axis which moved up and down according to the force used by the pistons and the forces of their weights increased when they were lifted or lowered, in the same ratio as a compressed spring[461]. The temperature could not affect this clock just as it had affected the previous ones. In another drawing, Huygens showed a different way of keeping the isochrony of the pendulum by positioning the piston between two pulleys, which were moved by an axis with two weights similar to CD in the figure above. This Huygens called the *Hydragyrum.* (P in figure 31).

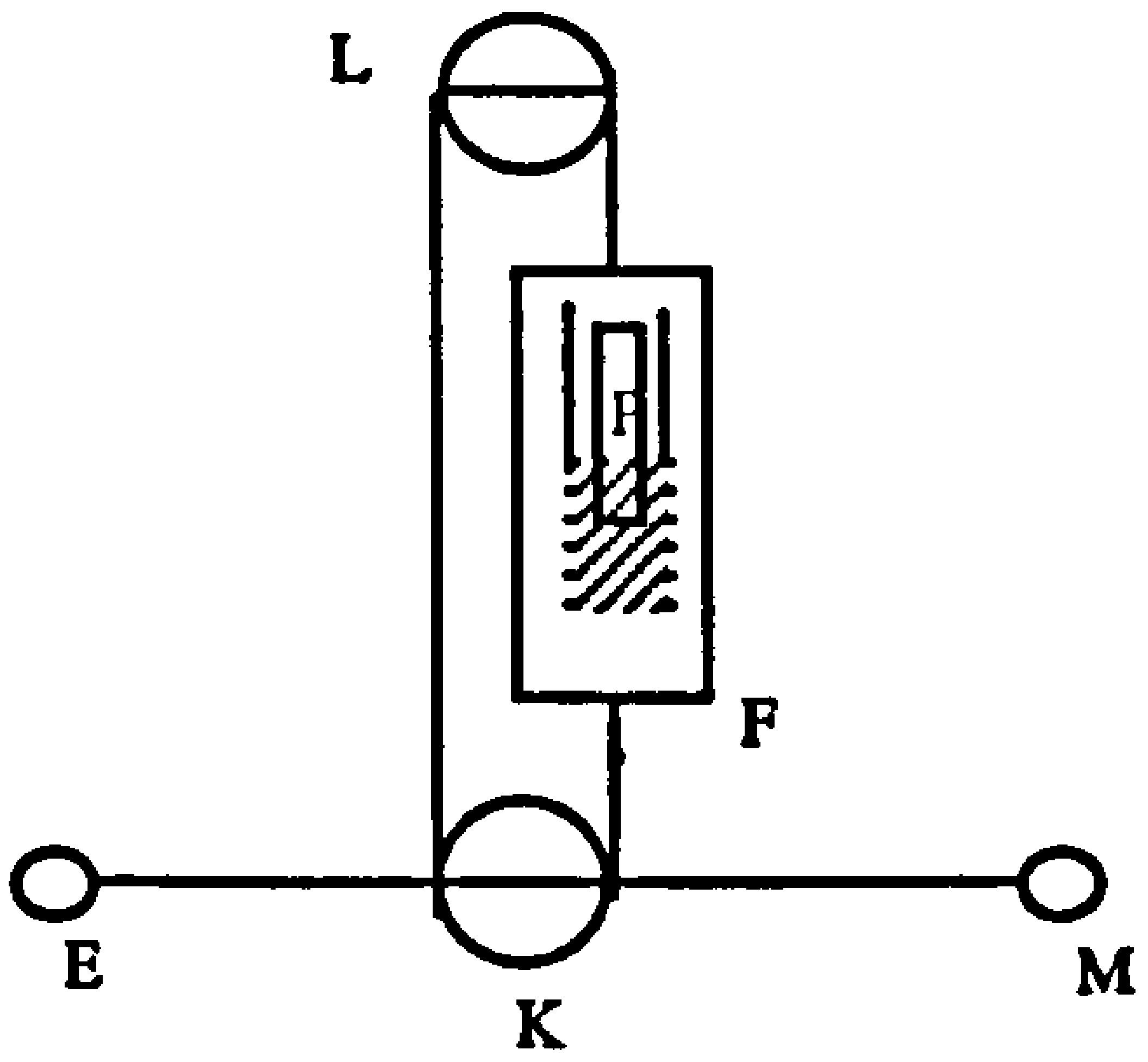


Figure 31 - Another type of marine balance, further developed in 1693[462].

This perfect marine balance (figure 31) appeared in the designs and marine clocks of 1693. Several figures were drawn following those of 1683-4. It was further improved with the introduction of chains to assure the isochrony of the oscillations[463]. This system reduced the friction in the clocks and kept them going for longer. The clock was suspended from an iron frame and a weight held the clock to keep it straight and more balanced[464].

It was a very advanced design with which he came closer to physics. However, it had its limitations. Huygens was not able to deduce the physical formula to explain how the balancier worked, but he aimed at reducing friction, creating a continuous regular movement and reducing the action of temperature. This *balancier* was certainly advanced for the time and one that would prove once more Huygens as a mechanical engineer.

Huygens showed how to build the clocks of 1693 and how they should be suspended to keep them going regularly[465]. The cycloids were also used. He deduced that if the vertical distance from the circumference to the tangent was 1/4 the distance from that point in the tangent to the point where the tangent touched the circumference, then the pendulum at this point would weigh 1/4 its absolute (*absolu*) weight[466]. In this case, Huygens also insisted on having either a simple balance with a chain, or another clock to calibrate the clocks[467]. He deduced further geometrical ratios in the mechanisms of the clock[468]. Finally, he showed a more complete design of the *balancier* marine following the first designs of ten years earlier (see figure 32).

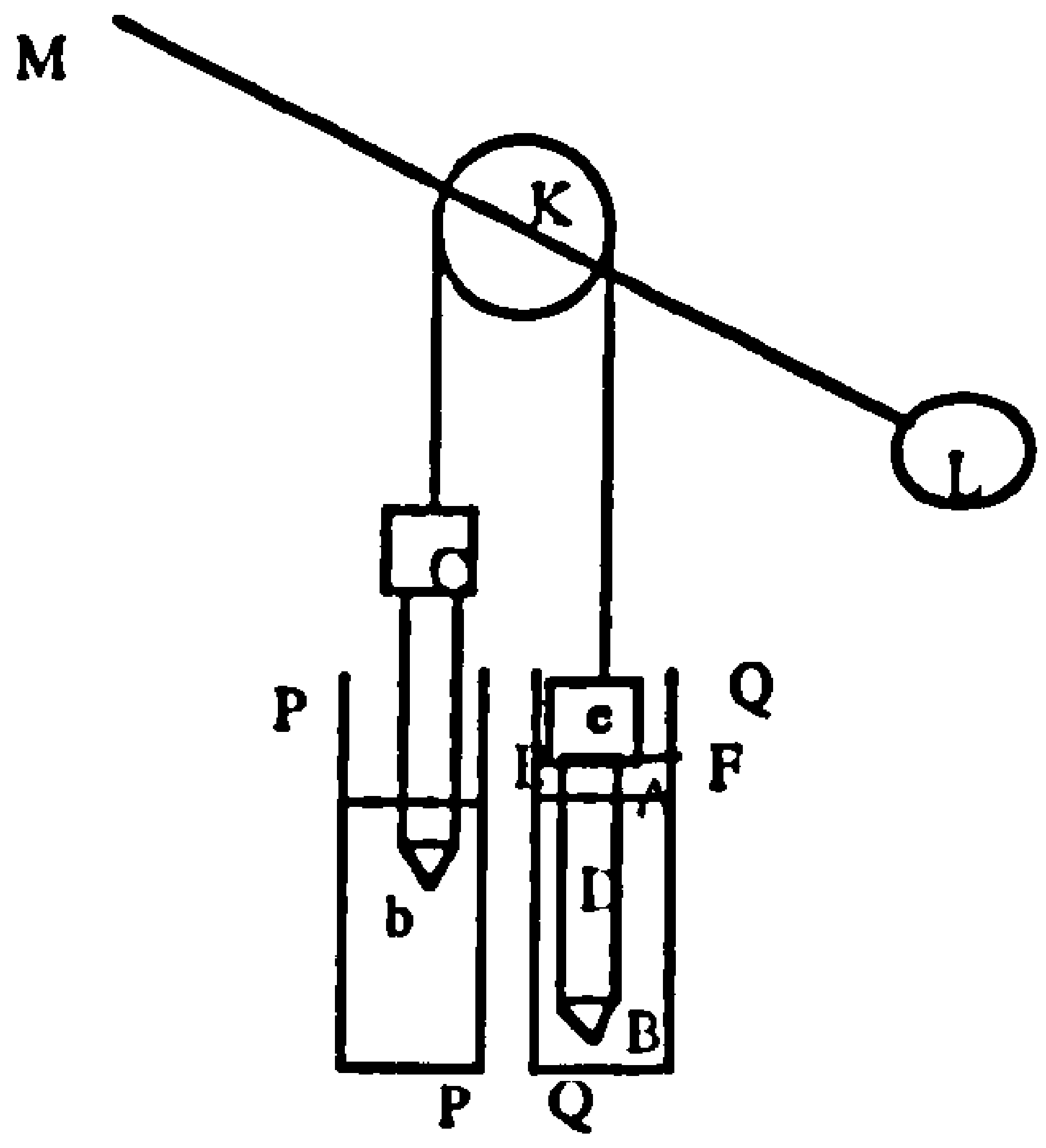


Figure 32 - The perfect marine balance of 1693 with two pistons[469].

Either with water or with mercury in the pistons, there was still resistance proportional to their weight. In figure 32, one cylinder descended and the other one raised when the *balancier* LM moved over K. The liquid in the cylinder would raise when one of the smaller cylinders was lowered, AB. The cylinders PP and QQ contained the *hydragyrum* and a cycloid was used to make the oscillations isochronous[470]. He said that it was necessary to take into account the friction due to the action of air upon the circumference K. A solution he proposed was to make a cross of iron inside an empty circumference.

This way it would be stronger and would support the action of the air better, reducing friction[471]. This is another clear example of the engineer since friction has always been an important factor of study in mechanics and, in particular, in engineering.

In June 1684, Huygens said that the cylinder built pendulum was more stable at sea than previous marine clocks[472]. At this time he was looking for a way to improve the triangular pendulum[473]. This clock was of *remontoir à ressorts.* In February 1684, there was a Resolution made by the Company of the Indes Orientales about a burgomaster, Hudde, who wanted to do the trials at sea with Huygens' clocks[474]. In August Hudde was appointed for that job[475].

Hudde reported on the results on September 17. They did not seem good to Huygens who decided not to use the clocks again at sea because of the way in which they were affected by the movement of the big ships[476]. In this trip, Huygens used two clocks[477] and even designed the way in which the clocks should be attached to the ship to keep them more balanced during the trip. A mobile frame of iron held the clock. This was an important design because with it the clock was better balanced and, more stable yielding more precise results. This is one more proof of the engineer working on the instrument and on other mechanical means to make it function better. The pendulum had the form of a triangle and a bob of lead suspended from it, then the clock was set in the frame of iron used to keep it balanced at sea (see figure 33).

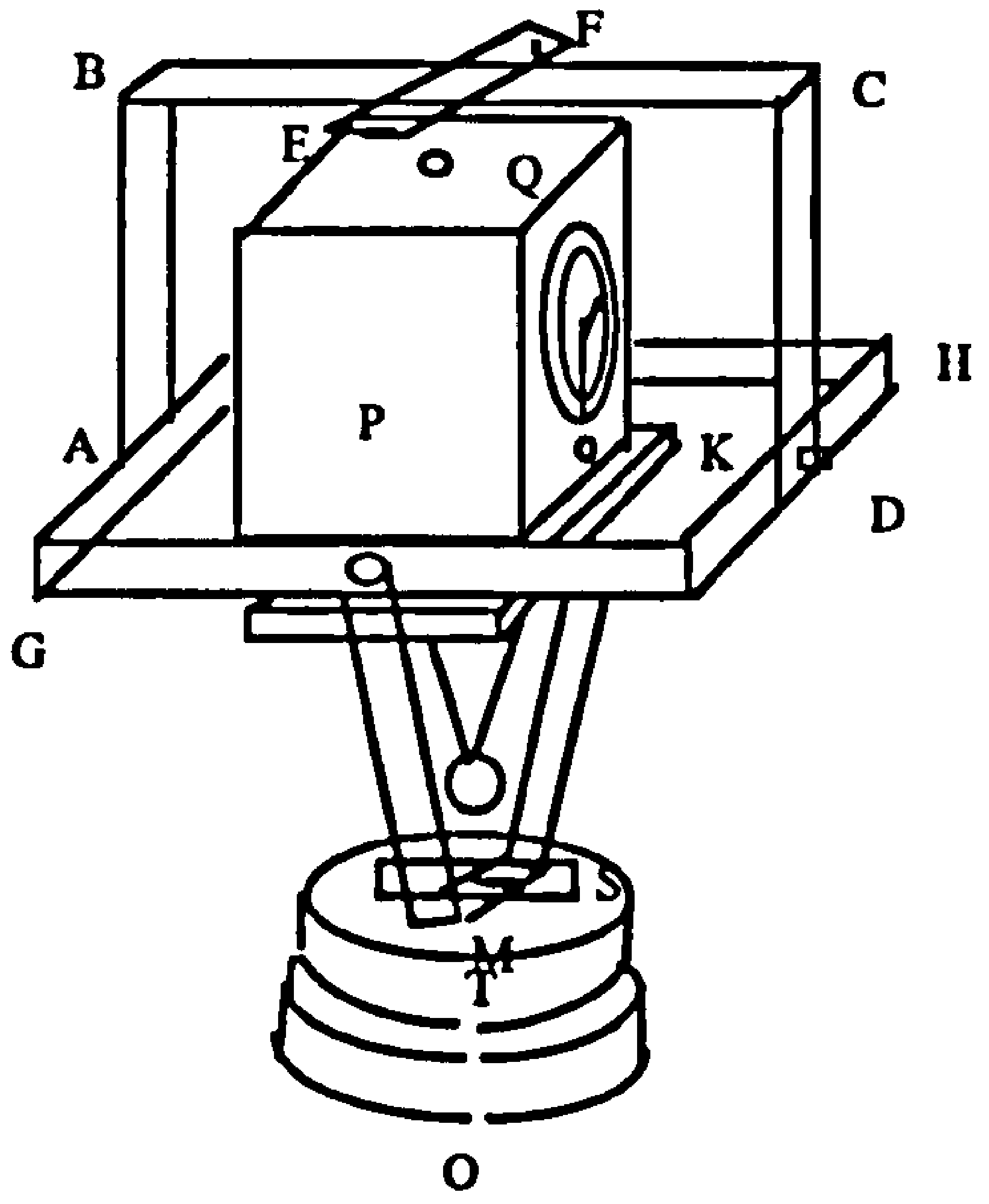


Figure 33 - Marine triangular pendulum clock with iron frame ABCD GH, with further support MSTO, to keep it balanced at sea[478].

Once more the design was accompanied by several guidelines to set two clocks and to keep them in good working order throughout the trip[479]. He drew it and explained it just like he had done with previous instruments[480]. Huygens was very happy with the work of Van Ceulen and praised it in his letters[481]. Coster used a *fusée* in the clocks of 1658. However, Huygens did not use it for the marine clocks of 1672[482], but introduced it in the 1680s again, and can also be found in the planetarium that Van Ceulen built for Huygens in 1682[483]. Huygens defined the formulae “$T = \pi \surd I\ Mgb$” for the compound pendulum and “$T= C \surd I$/the moment of forces for a determined angular space”, C was a constant, for the *pendulum cylindricum trichordon* (a triangular pendulum with a cylinder)[484].

Huygens sent a long report to the Directors of the Company of the Indes Orientales. It described in length the success of the voyage of 1686-7[485] they decided to fund another one in 1690-92. The clocks used were of the same kind as those of the previous trip[486]. In March 1693, Huygens said that the results were not as bad as they might have been[487]. He had designed what he thought was the perfect triangular pendulum, which could be applied to the clocks to improve their performance at sea[488]. The Company did not show more interest on the matter since no letters were exchanged after that.

There were some difficulties with the marine clocks attached to iron frames. The frame was not enough to stop the clock from motion at sea[489]. Also when the pendulum moved it transmitted a certain motion to the clock making its working more irregular[490]. The threads used to suspend the pendulum from were faulty, and the clocks were very complicated. A list of what should be done to improve them was given too. The clock should not have any springs, or *fusée*, but should be weight driven. More weights were added to the iron frames, since they did not seem to have held the clock so well in the trip of 1690-2[491]. With time Huygens thought that the marine balance was better than the pendulum for the marine clocks. This can be seen in those designed from 1692 onwards. The designs of March 1693 and 1694 included the balancier and the weight to drive the clock, but not the pendulum[492]. In October 1694 Huygens drew the last marine clock[493]. In a letter to his brother Constantijn of March 1695, he talks about another marine clock similar to the two mentioned above[494].

The observations and trials carried out with the clocks were well registered and they show a good relationship between Huygens and the clockmaker[495]. The clockmaker making these later clocks seems to have been B.van der Cloesen[496]. The clocks of 1685 were not accompanied by full designs like the marine clocks of the 70s or the pendulum clocks of the 50s and 60s. The descriptions found were in the texts of those years[497], in some correspondence[498], and in the expeditions of 1690-92[499].

Huygens developed very important laws of motion essential for mechanics and to explain an automaton. One important law was the proportion of the moment of forces of a pendulum oscillating around an axis and the angle of swing. The Motu Corporum contained the propositions to prove the impact of hard bodies and the principle of inertia and was published posthumously[500] because, although it had been written between 1652 and 1654, Huygens still wanted to complete the treatise with further demonstrations[501]. He was able to deduce the theory for the observed phenomena of bodies in either, rectilinear motion, such as the laws of impact and inertia, or circular motion: the isochrony of the pendulum.

Huygens' constant designs of parts of the clock for improvement are a proof of the engineer looking for a perfect working instrument[502]. The pieces he wrote in the 90s are a good example of the importance he gave to detail. He knew that the improvement of any small part of the clock would render a more precise instrument. This is the case of the designs made to find the right shape of the curve for the cheeks of the pendulum of 1658. He constantly worked to perfect the instruments with the help of designs and very often by experience. He applied this method to his works in mechanics, changing the parts of the clock he thought needed improvement, by designing them and testing possible shapes. Later on, he also used *balanciers*, to find the isochronism of the clock[503]. For instance, he made a good amount of calculations to correct the variation of the moment of forces in the *balancier* and studied its ratio with its axis. He arrived at the conclusion that the bigger the axis the less variation was observed. I do not think that he could have arrived at this conclusion without having built different *balanciers* himself[504]. Huygens believed in the conservation of forces in nature. He showed this in his first writings on the conservation of motion in impact[505] and in the pendulum clocks and in the marine balance later[506].

Towards the end of his life, Huygens still called Thuret a plagiarist stating that he had invented the portable clock against Thuret's claim of priority[507]. Also at this time, he said that the circular pendulum clock presented some drawbacks, but he did not explain them[508]. In general, Huygens' relationship with instrument makers appears to have been good since he regularly praised their work in the correspondence. However, he felt annoyed when they tried to cheat him by claiming patents for his own inventions.

4. HUYGENS AND THE INSTRUMENT MAKERS

In the seventeenth century some scholars made instruments for their own use and sold some of them. Huygens was a good example of this. His clocks were sold in different countries in Europe, mainly in The Netherlands, France and England. They were tailor-made, following the wishes of the buyer. Huygens' accurate lenses were well known by his contemporaries and he often sold them, whereas the clocks were mainly made by clockmakers according to his designs. Clockmaking was a well-established and often profitable craft. He also introduced new trials and experiments to ascertain their accuracy. The skills of Dutch clockmakers were learned by English counterparts. For example John Fromanteel learned Coster's clock making from 1657 until 1659. These clocks influenced English clocks for some years[509].

4.1. Coster and the patents of the 1658 clock

Coster was Huygens' first clockmaker. They maintained a good relationship and collaborated well. Coster's good work and good nature was known to his contemporaries. He made the first pendulum clock for the open market in 1657[510]. In June, Coster was granted the patent for Huygens' pendulum clock. The official patent was issued to Coster by the States General[511] who stated that Christiaan Huygens had given it to him[512]. The patent defined how the new innovation in the clock made it more accurate than any other clocks in existence before[513] and it also made the clock less vulnerable to changes of weather than any other[514]. The author was reassured that nobody would copy his invention as stated in the patent[515], otherwise, a penalty could be implemented[516]. The patent was finally granted for the period of 21 years excluding anybody else for those years and allowing Coster to make and sell the invention[517]. The official patent was granted from 16 June 1657 and with a protection of 21 years[518].

However, this was not going to be a straightforward business. A little more than a year had elapsed when other clockmakers, seeing the rewards of having an official patent, decided to claim a new invention with the smallest changes in the clock's machinery. Douw, from Rotterdam, was one of them. The long discussions in which Huygens had to engage to defend his patent against Douw were unpleasant, since he really cared about his invention and thought highly of his achievement and its utility.

Douw requested to the States General to be granted a patent because he claimed to have invented a new instrument[519]. Douw even claimed to have published the new invention in a journal. He said that he had invented a new escapement, a back and forward wheel and different from the one used by Huygens and for which Coster had obtained a patent. He emphasized how accurate clocks would become if his invention was applied and that it was[520] working better than any others until then invented[521]. The patent ends with the same official protection as Huygens', forbidding other people to imitate such work and granting the patent for the following 21 years from 8 August 1658[522]. Huygens had to summon Douw to the Courts because he was convinced that the latter had not really invented anything. He might, nevertheless, have improved the clock. To Huygens he was a mere plagiarist as stated in a letter to van Schooten[523].

In 1658 Coster addressed the States of Holland to complain about Douw's issued patent, which in his opinion was a mere copy of Huygens' clock. Coster and Huygens made a court appeal to the Dutch Courts[524]. Huygens expressed his discontent and anger on October 1658 to van Schooten[525] and to his cousin W. Pieck[526]. What annoyed Huygens was the continuous reference to a "new invention" in all the patents issued by the States General to Douw. Huygens asked his cousin to stand against Douw because if he lost the suit put against him, Douw's patent would automatically be cancelled. Huygens says in his letter that Douw had seen the clock at Coster's place, six weeks after Coster had obtained the patent. And that having changed very little in it, Douw pretended to have made a new clock. Even more, Douw wanted to join in the benefits of their patent[527]. When this was refused to him, he managed to trick the States General into giving him a new patent[528].

This fight over intellectual property of the patent was important to Huygens because, as we said before, had he won the lawsuit, Douw's patent would automatically be annulled. He was upset because of the time wasted in such a useless business, especially when the fight was over something good he had created[529]. Huygens did not trust those clockmakers working under Douw. When there were commissions for clocks Huygens mentioned a clockmaker in Nijmegen, Mr Jan Cal, who was going to bring to his cousin Pieck a model of Huygens' tower clocks. Huygens asked Pieck to receive him and see the description he carried on his behalf, and should not employ any clockmaker working under Douw for the construction of the comissioned clock[530]. Huygens was obviously in contact with several clockmakers to which he had explained his findings. He communicated to one of them the best way to do tower clocks. These clocks were found to be good by experience, whereas those of Douw had not been put to work anywhere[531]. In October 1658 Huygens wrote to van Schooten thanking him for the advice he had given him to use against Douw[532]. However, Huygens did not gain the suit and a patent was finally issued on December 1658 to Douw, as if he had invented something really new for the clock[533]. The same year, Huygens was thinking of asking for a privilege in France, as he wrote to Boileau[534] who raised the subject with the Chancellor. But it was refused so as not to annoy the French clockmakers[535].

Plomp's doubts about the full effect of the Coster-Huygens' patent[536] is open to objection in view of what I have discovered about Huygens. We have seen that Huygens reacted very quickly to any attempts to copy his clock. Moreover, he was convinced that a patent would protect his inventions. He obtained privileges in France in the 1670s for some inventions including the marine clocks. Furthermore, Plomp contradicts the previous statement when he says that Dutch clocks did not improve for 21 years because of Huygens' patent, which protected his clocks for that period of time[537]. In my opinion, there are two important points that need to be taken into account. First of all, Huygens was highly admired by Dutch clockmakers and after the lawsuit with Douw they must have been convinced that his were the best clocks. Furthermore, lawsuits were expensive. They simply did not think it necessary to develop the clock further if it worked well. Also a series of broken diplomatic relations and wars with England and France made dissemination of new ideas to The Netherlands difficult between the late 1660s and 1670s. These may be some of the reasons for the isolation suffered by Dutch clockmaking for almost 20 years, although some French Huguenots distributed ideas from French clockmaking throughout Europe.

4.2. Other instrument makers

Oosterwijck made clocks for Huygens after Coster. In 1660 Brouncker, president of the Royal Society, and Moray, received clocks made by him. The Huygens' brothers commented about his clocks with great admiration and he was often mentioned in their correspondence[538].

In the 1660s Claude Pascal was making clocks for Huygens[539]. Pascal was clockmaker in The Hague after 1654 and until 1674[540]. According to the editors of the Oeuvres, by 1658 Huygens had sent more than 50 clocks to Dutch, German, French and English people. They included learned men, aristocrats, amateurs and others[541]. Huygens wrote in his Journal de Voyage that he had visited him in London[542].

Already in 1658 and 1659, Huygens had applied the weights to the clocks and was very happy with the results[543]. Before the weight driven clocks -*à poids moteurs*- created by Huygens in 1664, there were clocks wound up by springs -*remontoirs à ressorts moteurs* [544]. Thuret's clocks were driven by a spring[545]. Huygens said that Thuret built his clocks following his advice, their driving spring was similar to some pocket watches Huygens had had repaired in The Hague with a *remontage d'heure en heure* [546].

From the beginning of the 1660s, there was a lively exchange of ideas and about new clocks with Chapelain. Thuret communicated with Chapelain in 1665, offering his services to make Huygens' marine clocks and to sell them[547]. Huygens was happy with this offer because he knew that Thuret was a good clockmaker[548]. Huygens created the clock with *remontoirs à poids moteurs à remontage d'heure en heure*[549]. However, Thuret soon claimed priority over this. Huygens had showed it to Chapelain in 1665[550]. But it is also possible that Chapelain did not really know what was the simple change Thuret claimed to have introduced in the clock. Huygens had said to Montmor that Thuret should see the clock[551]. There is a possibility that in 1665, Thuret might have made a clock with this system. Particularly so since Auzout communicated to the Dutch scholar that Carcavi had asked Thuret to make one following Huygens' model, just received[552]. Furthermore, Montmor had asked Thuret to show to the Academy how Huygens' clock worked[553]. When

Huygens was invited by Colbert in June 1665 to join the Academy, Chapelain advised Huygens to deal directly with Thuret on this subject since he was going to live in Paris[554]. Thuret's clocks had two weights, one above the other but they were fixed, unlike Huygens' which moved as a whole system connected by chains[555]. Was this what Thuret claimed was different from Huygens's clocks?[556].

But the problems did not end there. In 1675, when Huygens designed the spiral spring to make watches isochronous, Thuret also tried to claim the invention for himself. Once more Huygens was driven into long discussions about priority[557]. The same year, he wrote to his brother Constantijn[558] about how upset all this made him. These discussions must have been difficult and long, particularly because Colbert and his wife protected Thuret[559]. Later Thuret admitted he had not participated in the invention[560]. Although Huygens had praised Thuret's work[561], however, he did not mention him ever again after November 1675. In this letter, Huygens recognized that Thuret's had produced the best instruments until then[562]. This was the end of ten years working together. Thuret had been engaged to make clocks for the Observatory and the Academy since 1672, but he was already mentioned in writings of the Academy as early as 1669. In 1687, Thuret made some machines on the movement of the planets and was well paid for them.

In 1676 Oosterwijck also made clocks with a straight instead of a spiral spring[563]. But soon they became obsolete with the use of the spiral spring. The clockmaker Oosterwijck made and sold Huygens' marine clocks in 1672 following his instructions of 1665[564]. As with Coster in 1657, Huygens showed up to the end of his scientific career a good relationship with the clockmaker[565]. It seemed a normal thing for him to do, to treat instrument makers as collaborators, rather than as workers from an inferior class, as some people have stated giving hardly any proof for it and mainly speculating on the subject rather than following Huygens' clear and abundant correspondence[566].

From 1658 Dutch clocks influenced other European countries. However, when Huygens moved to France, French clockmakers started to produce some of the best models. In 1683 many Huguenots fled to the Netherlands, after Louis XIV had revoked the Edict of Nantes. Amongst the Huguenots who left France there were 37 watch- clockmakers that found refuge in Amsterdam. Then Dutch clocks were again in the forefront of clockmaking. This statement contradicts Plomp who gives more than twenty years of Dutch influence upon European horology. Johannes van Ceulen and Johannes Tegelbergh, who used the two-train movements, show the influence of French upon Dutch clockmakers. The fact that there was no guild of clockmakers in Amsterdam, must have made it easier for French Huguenots to settle there and, therefore, to keep their own way of clockmaking. Dutch clockmakers such as, Pieter Visbagh; Bernard van der Cloesen; or, Laurens van Blade, maintained the Dutch construction, based in Salomon Coster's model. They kept their going trains with 4 wheels, whereas, those with French influence had 5 wheels. Also they had a larger barrel than earlier clocks and the height of the plates increased from about 11cm to 13-15cm[567]. Two of the reasons given for their popularity are the public's preference for longcase clocks, as well as the improvements introduced on the designs at least every five years. In other words, they were of more advanced design, more accurate because of the use of the anchor escapement, and more sumptuous.

The clocks were mainly tailor-made for buyers who said what type of change they wanted in the clock. Huygens passed their message on to the clockmakers[568]. Huygens also suggested improvements to the commissioned clocks. Also unique to Huygens, when compared to contemporaries, was this very enterprising way of promoting his own work within and outside the scientific community. Dutch clockmakers continued the tradition started by Coster. After the early 1660s they do not seem to have brought any major changes to it. Although Huygens had designed the pendulum for a weight-driven clock, Coster produced a spring-driven clock with a pendulum instead of a balance. However, in 1664 Huygens improved the clock further, achieving a rewind of the remontoire every half-minute, which was not matched until 1761 when John Harrison got a rewind every 7 1/2 seconds.

Furthermore, the period of time of Dutch influence upon clocks could not be more than ten years. In 1670, Joseph Knibb (although attributed by others to Robert Hooke or William Clements) applied the anchor escapement to the clock. This escapement was directly attached to the pendulum and underwent a repetitive action motivated by the driving force of the clockwork, thus reducing the arc of the pendulum. The cycloidal cheeks were no longer needed.

Those commonly referred to as examples of seventeenth century natural philosophers also makers of their instruments include: Galileo, Scheiner, Torricelli, Cherubin, Pierre Borel, Hooke and Huygens[569]. History of science requires a finer analysis, rather than generalizations. They all had different ways of dealing with the making of instruments and they might have sold some of them, but not always directly. Hooke and Huygens for instance would be of two different categories. Hooke made different instruments, such as the air-pump and he sold them, but Huygens mainly sold his lenses, which had been made by him and participated in the profits of the clocks with the clockmakers as patent petitions show. One even more important difference that places Huygens in a unique place is his pioneering work as an inventor who drew designs for the instrument makers to follow, apart from maintaining direct communications with them. In this, amongst other things, Huygens resembled the "mechanical engineer" unlike any of his contemporaries including Hooke –whose work and influences by Tompion need further research. The pendulum clock and all its designs over more than twenty years was a very special example of it.

Huygens' relationship with the instrument makers was very different from that of other scholars of the time. He designed the instrument and as an engineer accompanied it with explanations and geometrical demonstrations, and passed it on to the instrument makers who collaborated with him at the time. The relationship between Huygens and the instrument makers was not one of 'gentleman' and 'servant' respectively, as some authors have stated, but one of an engineer who had new ideas and discussed the new designs with the professional instrument makers and for whom he held a constant admiration. It is only logical to think that the relationship with instrument makers had to be closer and better than it is been so far suggested. The differences between Huygens and the clockmakers appeared mainly when copies wanted to be made of a newly developed clock or when the instrument maker failed to perform Huygens' instructions. Huygens did not seem to realize that once a patent was accepted it could not stop others from applying for new patents even if the change introduced in the clock was minute.

Huygens did not mention certain instrument makers carrying out optical work because they provided the materials and were not mentioned by any contemporaries either. This would contradict some opinions[570]. It could be said that lens grinding was an occupation that some gentlemen borrowed from craftsmen. Furthermore, a comparison can be drawn between lens grinding and the clock. Huygens designed and invented the pendulum clock, a measuring instrument and deduced a mathematical treatise to accompany it. In the same way, Huygens was grinding lenses by hand, but he also thought of a machine that would make the grinding of elliptical lenses easier[571]. He accompanied the designs of this machine with a mathematical theory too[572]. He also designed bigger machines to grind big lenses[573]. What can be concluded from this? Huygens believed that any instrument could be improved, and that is why he drew them, accompanying the sketch with a mathematical treatment to provide the scientific basis needed to explain their design and operation. If Huygens had had disregard for manual work with certain instruments, as it has been suggested, he would not have bothered to make instruments to grind lenses, not models of clocks. Therefore, the statement that Huygens did not like manual work because of his rank can be strongly argued. It is hard to place Huygens within a 'scientific category' if one considers his interest in so many mechanical aspects of his instruments.

Therefore, Huygens did not disregard manual work as inappropriate since he made models of his inventions before he even made the designs for the clockmakers. No sharp separation should be made in the seventeenth century with the instrument makers as far as social class is concerned because nobody knows much about the status they had in society, specially since some of them enjoyed a good turnover from their clockmaking, e.g. Tompion. What annoyed Huygens most was the fact that a clockmaker could claim a patent without inventing anything new, by simply introducing a small change in the clock (Douw, Thuret). Huygens and Coster collaborated closely improving the clock and without problems. The same can be said of most of the other clockmakers. Coster was well known to some of Huygens' colleagues who said he was a man of good will[574], and made many clocks for them[575]. The clocks were prized according to how sophisticated their machinery was[576].

Huygens obtained several privileges for his new clocks in 1675; he applied for a privilege to Colbert at the beginning of the year, for portable land and sea clocks[577]. In February, he obtained the privilege[578]. The States of Holland gave Huygens several privileges the same year and on 25 September, he obtained one for fifteen years for an invented marine clock, still not built[579]. Two days later, he obtained another one for pocket watches[580]. His father, Constantijn, used his influence to obtain these privileges since there was pressure from others to gain patents for clocks, to find the latitude of Paris[581], the position of the fixed stars[582] and also longitude.

5. EXPERIMENTATION: SCIENTIFIC CONSEQUENCES OF THE INVENTION OF PRECISION AND PHYSICAL INSTRUMENTS

Huygens had tried and proved with Coster's help that the clock had become a good timekeeper by applying the pendulum. With a better instrument, experimentation could be carried out and would benefit astronomy and longitude too. Huygens knew the impact that his work could have upon science and how important the use of the clock at sea would be for the French Court and its use for society in general.

By applying the pendulum, Huygens had created the first accurate instrument for measuring time. And by designing and changing different parts of it, he improved its functioning and, therefore, its precision. According to Sydenham a division of instruments used for measuring can be drawn. The clock should take a leading role in the field of instruments of precision.

How much of the success of an experiment can be attributed to an instrument? Hackmann says that once an instrument was found to be able to perform a specific role in experimentation, with more or less success, the problem was to replicate the experiments with that instrument. Although Hackmann is referring to eighteenth-century science, this can also be applied to the second half of the seventeenth-century. Physical and natural phenomena were studied at two levels: instrumental and philosophical. As new phenomena were observed, they influenced the design of instruments[583]. However, Huygens was the link between a philosophically rooted science and the modern one mathematically- and experimentally-based. The explanations of the results found with the instruments were not only philosophical, but they were purely mathematical. Huygens was the first natural 'scientist' to write a treatise in mechanics, which described automata in mathematical terms.

As Schaffer states "experimental controversy involves contest about authority". Through a series of trials the experimenter will convince those attending his performance. The improvements of any instruments used to perform an experiment were essential to obtain better results and so convince the public attending such an experiment[584]. The aim was to convince the audience. It could be added that the experimenter had to convince his own scientific community first. This was possible only if he could show that the results obtained with new instruments were better than those obtained previously. The best example of this was the air-pump. In the case of the pendulum clock debates seemed to be settled according to whom knew more about the instrument. Huygens had invented it and his rational conclusions convinced the scientific community that he was right. Maybe they should have carried the arguments further. However, very few knew the clock and the mechanics of its functioning as well as Huygens did. Therefore, they believed he had the best explanation and nobody seemed to have a better alternative.

Bennett classifies seventeenth-century instruments into mathematical, optical and natural philosophical, in order to understand better both contexts, the theoretical and the practical. This division was already used in the Seventeenth century[585]. What Bennett seems to omit is that there were also mechanical instruments, called at that time automata as Huygens called the clocks, and not mathematical machines[586]. Automata because they constantly reproduced the same motion in each oscillation of the pendulum and they became the first precision measuring instruments.

Cantor says that only from the seventeenth century onwards has nature been interrogated directly to find the truth. As he asserts, historians should search for more than texts, also for the role-played by experimentation[587]. Experimentation has been a good tool for learning and training, apart from its importance for the advancement of science. However, it could be argued that Huygens did not have a developed experimental discourse, whereas Boyle did and that Huygens only defended his cases for priority in mathematical terms. However, the chapter on matter theory will reveal a sophisticated 'philosophical discourse' based in the physics of the time, also in the theories of some classics and on his own[588].

Gooding, like Shapin, believes that experiment aids first of all to construct experience and then to theorise the experiment. The works of nature could be shown in experiments[589]. It is true to say that experiments help scientists to know more about nature. Furthermore, they have acquired, since the seventeenth century, an important role proving hypothesis and developing the subsequent theories. Gooding says that this role played by experiments became important because of the social status of those who carried out the experiments. It could be added that they became important because they could be replicated and many people could acquire the skills to do so. Hence the development of different scientific groups from technicians to assistants, or specialists.

Shapin for instance says that people in the seventeenth century believed people according to who they were[590]. However, those who were, were normally those who knew. Also according to Shapin, Boyle wanted to express the new science in an appropriate rhetorical form: explaining them clearly to any reader. But more outstanding in Boyle's writing was the witnesses in the experiments that allowed the reader to be persuaded by the adequacy of the experiments and of the facts found.

6 CONCLUSION

Huygens' idea of applying the pendulum to existing clocks was a clever and successful one and was admired by contemporaries interested in corresponding with him[591]. The scientific community acknowledged Huygens as the inventor of the pendulum clock, in that respect it was a fixed event[592]. He did not have to make the whole clock because there were already clocks available. What he had to do, and did, was to perfect the machinery of the existing clocks and add to them what would make them more accurate and precise, the pendulum. But, most importantly, he had created the first reliable precision instrument for measuring time that could be used by astronomers and the experimental sciences. The pendulum clock was the first dynamic system ever studied[593] and this is what Huygens developed fully in his Horologium Oscillatorium. He was a mechanical engineer because he wrote the first treatise of a mechanical design, that of the pendulum clock, with an explanation and accompanying theory that became the mathematical foundations to be learned by anybody who wanted to become an expertise.

The work on clocks is clear evidence of Huygens' attempts to explain automata merely through mechanics and geometry, without a philosophical discourse. Huygens also made sure that his instruments were accompanied by instructions to use them or to build them: i.e. marine clocks, becoming a standard procedure from then on for scientific instruments and larger machines. He was able to state how much he had improved clocks in general and developed a variety of new models. His empirical work and the designs made him a pioneer engineer of measurement instruments. The clock was made to order. Also, the Horologium Oscillatorium was the first book on a measuring instrument with a design accompanied by mathematical axioms. The design was not composed of three planes but a side section only. This was enough for clockmakers from a long-established tradition of clockmaking. It must have been very easy for clockmakers to make accurate changes from direct discussions with the inventor.

The pendulum clock is a measuring instrument and was improved regularly to achieve an accurate timepiece. Maxwell says that: "everything which is required to make an experiment is called apparatus. A piece of apparatus constructed especially for the performance of experiments is called an instrument"[594]. This can be applied to the pendulum clock. Observation and accuracy are related, because an instrument will be defined as more or less accurate according to the results observed. Furthermore, the longer the time observed the better to define its accuracy, as well as the definition of new propositions in Huygens' geometry: the deduction of circular error and the cycloidal path[595]. However, the cycloidal cheeks became less used in the 1680s due to the invention of the anchor escapement.

It is important to distinguish two types of clocks: experimental clocks such as the first clocks designed by Huygens, and everyday clocks. Those made for experimentation were used to observe new changes in them and improve them accordingly; whereas those sold and made by Coster following specific designs of the buyer were used daily. There were several corrections in the clocks of 1659 and in the later marine clocks. Bruce, Thuret, Oosterwijck and Pascal made them in several European countries, in France, Holland and England. Many of the clocks made for experimentation in the search for accuracy and precision never reached the market place. Their value was merely empirical and their function experimental to aid to improve new clocks which would be produced to order if they were accurate and precise enough, or be more stable at sea if used to measure longitude.

The 1660s were happy years. Huygens felt optimistic when he discovered a new device that would improve his instruments, or would allow him to obtain a patent. The way he expressed this optimism shows how important it was for him to obtain more and better instruments. In 1663 he said in a letter to Moray that he had improved the marine clock[596]. Later, in February 1664, he wrote to Johan de Witt about the new winding weights he had introduced to improve the mechanism of the clock. In February 1665, Huygens quoted in a letter to Chapelain, Holmes' reports on the utility of the clocks and showed his optimism again when talking about the new chain clocks[597]. Furthermore, he knew the impact the clock was having in society too because it was available for the public in the open market.

Koyré says that, unlike Mersenne, Huygens searched for scientific precision by giving a theoretical basis to any results obtained in practical experiments with the instruments. This was the aim of the trials at sea in order to find a portable clock that would still be precise during a sea voyage. With Koyré and Mahoney I believe that Huygens' first precise pendulum clock was invented through trial and error and, sometimes, before deducing any theory for it. As Koyré concludes, in 1659 Huygens found what he was looking for, "an accurate clock to measure the exact value of the oscillation of the pendulum he was using in his experiments" and achieved this through theoretical mathematics[598].

Huygens carried out experiments on the clock and after seeing the results of the accuracy introduced, he developed a mathematical theory to explain them.

For the measure of longitude two things were important, clocks and the table of the equation of time, used to calibrate the two clocks normally carried on the ships. Huygens thought that sympathetic motion was the right way to calibrate clocks and keep them going constantly on the same train. However, he failed to question the causes of this sympathy when the clocks were close together. He obviously misjudged some of the inherent properties of his invention. The scientific society did not argue against him because they believed he knew about his own invention more than anybody else did. That is why this debate was very quickly settled following Huygens.

Huygens' greatest mechanical achievements as a pioneer of what later became a new field in engineering, mechanical engineering, were the pendulum clock and the two treatises with the geometrical theory to explain it of 1658 and 1673. Huygens created the first text in mechanics not only to elucidate the functioning of automata but also to show how to make them. The chain/weight-driven clocks must be added to these mechanics. This system also inspired an important geometrical theory of a system of pulleys and weights. Another important achievement was the spiral spring for watches and the balance of the spiral spring for marine clocks. Nowadays with the advent of computer-design, hand-drawing in engineering is not as important, but the description of the machine is still given.

Instrument makers understood a simple drawing or direct explanation to carry out the appropriate changes in a new device. Some of the theoretical work accompanying scholarly work of the seventeenth century was not necessary to explain the functioning of an instrument, but to give prestige to that scholar. This was the case of the studies on evolutes that Huygens added to the Horologium Oscillatorium, because as he had said, they were beautiful[599]. He did not know how important they would become over the years deriving later in a new discipline: algebra.

Huygens' work on clocks falls into distinct categories. First of all, in 1657, there was the making of an instrument with which time could be measured precisely and accurately, by adding a pendulum to a table clock. A second stage of his work developed in 1659, when he deduced the cycloid, which made the pendulum isochronous. A third stage in the 60s was the building of and experimenting with marine clocks, from three-foot-long marine pendulum clocks, to chain clocks. The fourth stage was the publication of the Horologium Oscillatorium in 1673. A fifth stage was in 1675 when he invented the spiral spring, and his dispute over priority with Hooke. Finally, the 1690s, when Huygens was still rewriting some propositions to the Horologium Oscillatorium, also some marine clocks and writing more polemical work.

Huygens broke away from the traditional mould of mechanics. He developed the Horologium of 1658 and the Horologium Oscillatorium of 1673, which represent the best and unique examples at this time in history of theories to support the works of a precision instrument. In the new tradition instruments would have to be accompanied by the corresponding theory to allow future inventors and engineers to design instruments based in known laws/theories. It would no longer suffice to work only on one field: for instance Stevin's work on statics, Galileo's on dynamics, or Hooke's on the air-pump. In the emerging field of mechanical engineering, adding a bit of an improvement to an instrument (Hooke) was not enough. In later centuries, the ingenuity to create, manage and design new instruments would also demand a full understanding of the theories of those instruments under study.

Huygens was the bridge between the older tradition of mechanics and the emerging new science within which he was the pioneer of mechanical engineering. In the old tradition, mechanics and physics had still a philosophical basis from which the new tradition of modern science moved away creating a new foundation of universal laws, and which culminated, later in the century, with Newton. But was Huygens able to explain the air-pump with the same clarity?

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[1] (And not physical as it has sometimes been stated, because physics did not exist as an independent branch of science yet).

[2] (Usher A history of Technology , Vol. 3, p.344).
[3] (Hall, Technology and Culture , 2 ,1961, pp. 334-5).
[4] (Musson, A.E. Science and Technology in the Industrial Revolution, 1969, pp.26-30).
[5] (Pacey, A. The Maze of Ingenuity , 1980, pp.131-2)
[6] (For water works using Archimedean screws for copper mining in Roman Spain in 1000 BC see: Williams, T.I. The history of invention from stone axes to silicon chips, Macdonald & Co, 1987. For some early engineering work in Greece in the first century A.D. see: Lewis, M.J.T. The Greeks and the early windmills, Hist. Tech. 1993, Vol.15, Mansell, pp.141-189).
[7] (Cooper, J.S. For Commonwealth and Crown: English gunmakers of the seventeenth century, Wilson Hunt, 1993. For the first gunpowder blasting in 1572 in mining Europe see: Hollister-Short, G.J. Gunpowder and mining in sixteenth- and seventeenth-century Europe, Hist. Tech. 1986, 10th annual volume, pp.31-66. Edited by N.Smith. And for ballistics see: Merton R.K.: Science, technology and society in seventeenth-century England, N.Y.1970).
[8] (Bennett, J. Geometry and surveying in early seventeenth century England. Annals of Science, 1991, Vol.48, N.4, pp.345-354. Johnston, S. Mathematical practitioners and instruments in Elizabethan England, Ann. Sci., 1991, 48, pp.319-344. Willmoth, F. The genius of all Arts and the use of instruments: Jonas Moore (1617-1679) as a mathematician, surveyor, and astronomer. Ann. Sci., 1991, 48, N.4, pp.355-365).

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[9] (Maanen, Jan van. Seventeenth century instruments for drawing conic sections. Mathematical, 1992, Vol.76, N.476, pp.222-230. For mathematical practice in the seventeenth century see: Mancosu, P. Philosophy of mathematics and mathematical practice in the seventeenth century. Oxford U.P. 1996).

[10] (Beard, G. The Work of Christopher Wren, Bloomsbury Books London, 1982).

[11] (For tools to work wood and metal in Sweden see: Knutsson, J. A seventeenth century collection of rose engines and tools: notes on the turning room at Skokloster, Sweden. Tools and Trades, 1990, Vol.6, pp.10-22. In 1662 London provided Sweden with lathes and iron tools. For Dutch ship decoration: Hoving, A.J. Seventeenth century Dutch ship decoration. Model Shipwright, 1988, N.64, pp.30-34).

[12] (European technology influenced Japan in the seventeenth century. It developed mainly in families, in particular, the industries of silk and cotton. Morris-Suzuki, T. The technological transformation of Japan: from the seventeenth century. CUP, 1994).

[13] (Sung, Y-H. Tien-Kung K'ai-wu: Chinese technology in the seventeenth century, P. U. P., 1966).

[14] (Maffioli, C.S. Out of Galileo: the Science of Waters,1628-1718. Rotterdam: Erasmus Publishing, 1994).

[15] (Dr.Morgan edited, published by Dr. Samuel Clarke, in Notes upon Rohault's Physics, Six philosophical Dissertations, Cambridge, 1770, On Huygens' cycloids, pp.28-37).

[16] (Mahoney, Boss edit. Studies on Ch.Huygens, 1980,p.235).

[17] (Vol.2, p.267, 459).

[18] (Sydenham, 1989).

[19] (Daumas, M. Scientific instruments of the Seventeenth and Eighteenth Centuries and their Makers. "The Invention of the Seventeenth Century". London, 1972, pp.27-88).

[20] (Vol.5, p.9; Vol.17, p.102-5).

[21] (Dugas, R. A History of Mechanics. N.Y.1988, p.181).

[22] (Bedini, S.A. The Pulse of Time: Galileo Galilei the determination of longitude and the pendulum clock, [Firenze]: L.S.Olschki, 1991, p.34-41).

[23] (Needham, J. et al, Heavenly clockwork, Cambridge U.P.1986, p.6).

[24] (Alfonso X el Sabio, Libros de Saber de Astronomía, edited by Manuel Rico y Sinobas, Madrid, 1866, Vol.4 which contains the making and designs of five types of clocks (*relogios*): *de la piedra de la Sombra; del agua; del argento vivo; de las candelas; del palacio de las oras*. A reference is made here to the third type: *dell argento vivo*, pp.65-76).

[25] (Drake, S. Galileo at work: his scientific Biography. N.Y. Dover Publications, 1995, p.419).

[26] (Bedini, The Pulse of Time, 1991, p.41).

[27] (Vol.18, p.63).

[28] (Vol.17, p.55).

[29] (Brusa, Orologi Europei Milan, 1978, pp.115-134).

[30] (Huygens' Horologium, translated by Ernest L.Edwardes, in Antiquarian Horology, Vol. VII, Dec 1970, pp. 40-4).

[31] (Bruton, E. The true book about clocks, 1957, p.41 and in The History of Clocks and Watches. Orbis Publishing, 1979, p.220).

[32] (Vol.17, pp.44-51).

[33] ("les astronomes ont commencé à utiliser les pendules, s'imaginera facilement que ces pendules d'astronomes ont fourni l'occasion de notre invention", Vol. 17, p.54. Boulliau wrote to Leopold de Medicis about this in order to clarify the latter's belief that Galileo had been the inventor, Vol.2, p.531).

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[34] (Plomp, Spring Driven Dutch Pendulum Clocks, 1657-1710, Schiedam, 1979, p.17+).

[35] (Vol.17, p.55).

[36] (Galileo, G. Dialogo, Vol.7, 1632, p.253; Discorso, Vol.8, p.141, edited by A.Favaro, 1890-1907).

[37] (Vol. 17, p.4).

[38] (Britten, 9th edition, p.72; Galileo, Opere, Favaro, Due Massimi Sitemi de Mondo. Vol.7, p.253).

[39] (Vol.17, pp.52-73).

[40] (Vol.17, pp.62-3, 68-9).

[41] (Vol.18, pp.68-368. The theorems on centrifugal force are in pp.366-368)

[42] (Britten, 1977, p.72)

[43] (Vol 17, p.55).

[44] (Slandes, 1983, p.118).

[45] (Plomp, 1979, p.16).

[46]

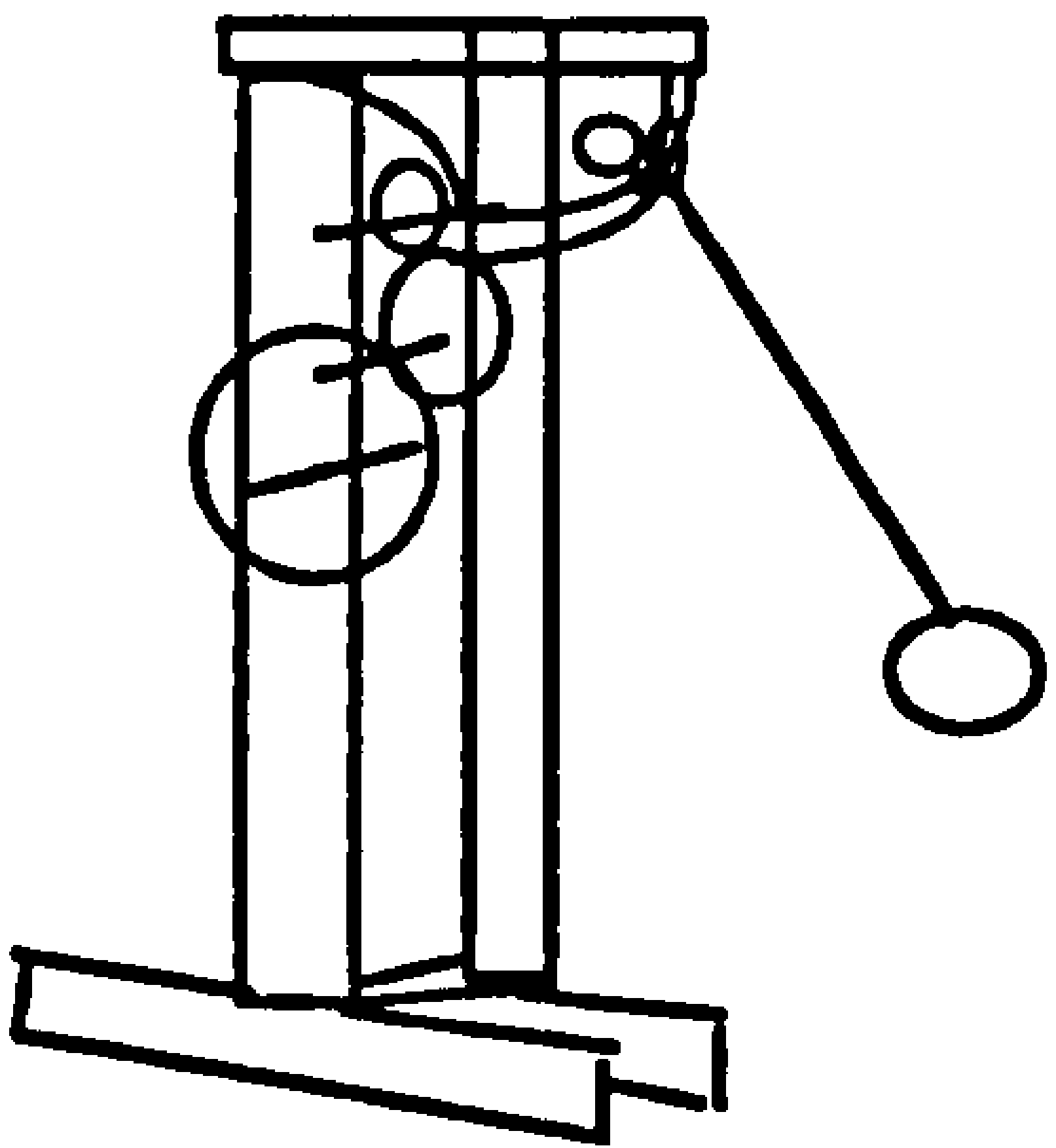

Figure 1. Working model, spring powered of Galileo's pendulum application, from the 1883 Science Museum model.

[47] (Vol. 2, p.35 and p.46).

[48] (Nicholas Boileau: he trained in Law and Theology, dedicated to literature. In 1672 he was historiographer to Louis XIV together with Racine. He was admitted to the Academy in 1683).

[49] (Vol.2, p.531).

[50] (Vol.2, pp.403-4).

[51] (Vol.2, pp.405-6).

[52] (Vol.2, p.413).

[53] ("Monsieur Wallis m'a aussi escrit (vol.2, p.296-308) qu'en Angleterre il y en avoit qui avoyent trouvé moyen de faire conter les vibrations du pendule par quelque instrument de sorte que la pensée semble avoir estè assez commune" Vol.2, p.405, and p.432 for the direct letter to Leopoldo de Medici).

[54] (Vol.2, p.441).

[55] (Vol.17, p.46-7).

[56] (Vol.17, pp.200-201, and Horologium, translated by Ernest L Edwardes in "Antiquarian Horology", Dec 1970, Vol. 7, pp. 40-4).

[57] (Howse, D. The Tompion clocks at Greenwich and the dead-beat escapement. Antiquarian Horology, Dec.1976, pp.18-34).

[58] (Vol.5, p.92, 263).

[59] (Vol.2, pp.237-242).

[60] ("because those clocks, whether large or small, they keep going, provided they are wound up" Vol.2, p.240).

[61] (Vol.17, p.14).

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[62] (From 31st of May to 6th of June Huygens registered the clock to be 2 minutes late, that is two minutes in 6 days, Vol.17, p.20).

[63] ($2T = 2\Pi \sqrt{l/g}$, Vol.17, p.15).

[64] (Vol.17, p.20).

[65] (Vol.2, pp.271-3).

[66] (Vol.2, p.531).

[67] (Plomp, 1979, p. 12).

[68] (Vol.2, p.280).

[69] (Britten, 1977, 9th edition, p.74).

[70] (Mersenne to Ch.Huygens, 8th January, 1647, Vol.1, p.52).

[71] (Vol.2, pp.104-110).

[72] (Vol.1, pp.18-9, 22, 24-27, 31, 558-9).

[73] (Vol.1, pp.47-48, 50, 54-5).

[74] (Vol.1, p.93).

[75] (Vol.2 -supplement- p.545-6, 564, 570).

[76] (Vol.1, pp.72-4).

[77] (Vol.1, pp.75-9, 91).

[78] (Vol.17, pp.125-137).

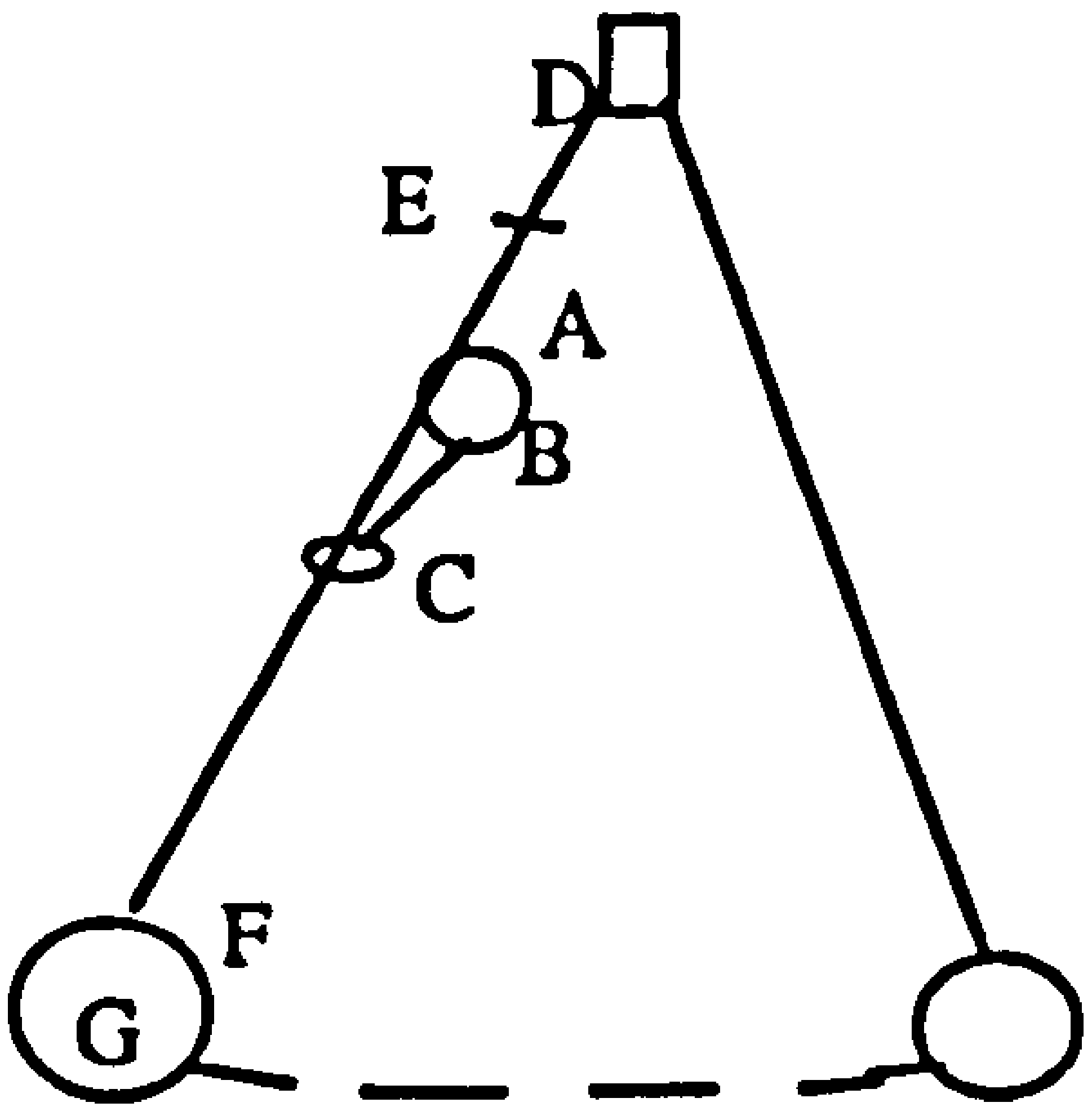
[79] (Vol.18, pp. 124-149).

[80] (Vol.16, pp.392-413. Vol.17, pp.97-113, 139-141. Vol.18, p.p100-203).

[81] (Vol.18, Part II).

[82] (Vol.17, p. 285-6).

[83] (Figure 6 - The pendulum of the 1657 clock and explanation of how it worked.



The balance wheel AB of a normal clock is perpendicular and by the action of the cord DF oscillates because the cord of the pendulum is passed through a thread of copper pierced at the end C. The bob of the pendulum G hangs from the cord DF. This way when the pendulum moves, it sets in motion the balance wheel but does not touch it. And since the balance wheel will have constant movements so will the clock. Huygens goes on saying that in his clock the cord of the pendulum DF is of 6 French inches. But the one in the village of Scheveningen was of 24 French feet with a bob of 50 French pounds. For even bigger clocks like that of Utrecht a different system was created. The clock was weight driven as it is explained in the text, Vol.2, pp.160-1, also described in Plomp, Dutch clocks, 1979, p.11).

[84] (Vol.17, p.103-5).

[85] (Vol.17, p.66).

[86] (Vol.2, pp.46-7, 188, 201, 212-4).

[87] (Usher, A History of Mechanical Inventions, N.Y., 1988, p. 312).

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[88] (Vol.17 p.53. Vol.16 pp.344-9, 392-412).

[89] (40 seconds a day for an arc of 10°. Bruton E. Dictionary of Clocks and Watches. Arco Publications, 1962, p.42).

[90] (Lloyd, H.A. Some Outstanding Clocks (1250-1950), London, 1958, p.74)

[91] (Yoder, Unrolling time,1988, pp.72-3).

[92] (Vol.17, p.65).

[93] (Letter to Petit of 1658, Vol.2, p.272, Teeth found in wheels and pinions: Weel L =25; E & H = 72; P (partially toothed)= 20 Pinions; G & K= 6; pinion O= 10).

[94] (SIT = 10/12 pieds with a simple vibration in a semisecond: 10/12 x 31.38 = 26.16 cm; Vol.17, pp.58-60).

[95] ("l'addition du poids fasse haster le pendule, que au contraire elle le rend tant foit peu plus lent, luy donnant un mouvement plus large, tout ainsi que du simple pendule les coups qui s'eloignment le plus de la perpendiculaire sont plus lents que les autres, et mesme pour remedier a ce defaut contraire a celuy que vous craigniez je suspendois du commencement le pendule entre deux platines courbes comme AB, CD, que l'experience m'apprit de quelle maniere et combien je devois plier, pour esgaler entre eux les coups des plus larges jusqu'aux plus me nus', Vol.2, 1st Nov.1658, p.271.

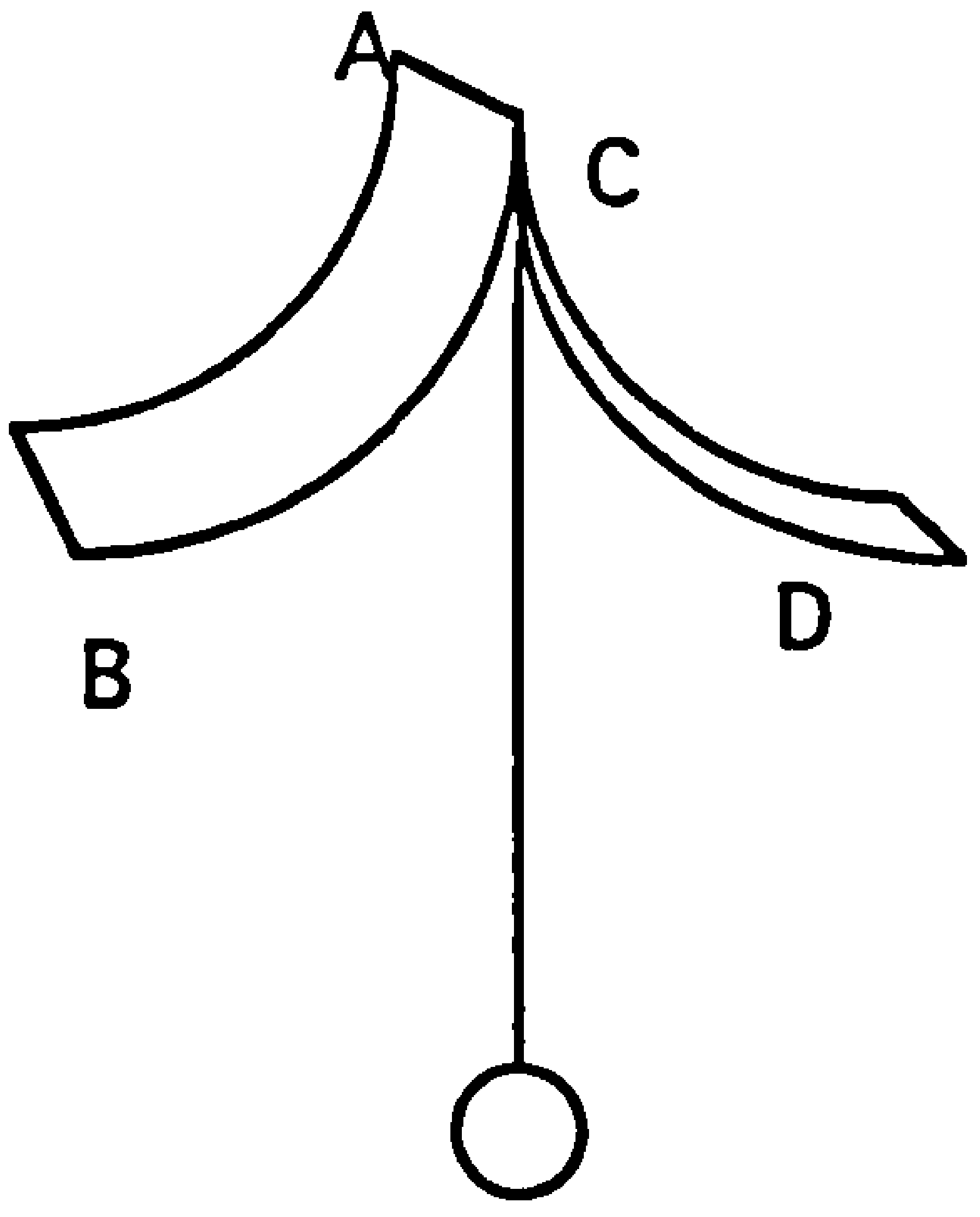

Figure 7- The arcs of 1658.

"Toute fois par apres parce que je trouvois que avec ces platines la moindre inclination de l'horloge alteroit la longueur du pendule, je les ay cassees faisant devenir en mesme temps les vibrations du pendule plus estroites, par le moyen des roues P et O, ce qui les rend plus esgales entre elles, et ayants besoin de moindre force pour estre entretenues").

[96] (Usher, A.P. A History of Mechanical Inventions, N.Y. 1990, p.304).

[97] (In: Libros del Saber the Astronomía de Alfonso X el Sabio, 1276-7. Daumas, M. Histoire Générale des Techniques, P. Universitaires de France, 1965, Vol. II, p.293).

[98] (See figures 6 and 7).

[99] (Vol.17, pp.64-5).

[100] (Vol.17, pp.66-6)

[101] (For big clocks also see Vol.2, p.161-2; Britten, 1977, p.241).

[102] (Vol.17, pp.68-69).

[103] (Mahoney, 1979, pp.238-9).

[104] (Vol.17, p.28. The number of teeth of the wheels differ from the clock of 1658 to that of 1657 as follows:

	1657	1658
Wheels:	E, H, L, O, P	E, H, L, O, P
Teeth:	96, 80, 30, 20, 60	72, 72, 25, 10, 20

Pinions G, K, V, have 6 teeth in the Horologium of 1673, but here they have 8. But, still these changes in the mechanism of the pendulum did not make it much more accurate and Huygens looked for the isochrony of the pendulum mathematically. He found it in 1659, which, as it is been said before, consisted on making the pendulum follow the path of a cycloid, he derived the cycloid in 1659).

[105] (Vol.17, p.70, note 1).

[106] (Vol.17, p.72; Vol.3, p.13; Vol.18, pp.90-1).

[107] (Vol.3, p.438).

[108] (Vol.17, pp.72-3).

[109] (Vol.2, p.271).

[110] (Vol.17, p.75)

[111] (Vol. 17, p.59+).

[112] (Vol. 17, p.58, note 3).

[113] (Vol.2, p.522).

[114] (Vol.17, p.88).

[115] (Vol.7, p.431).

[116] (Vol.16, p.254-318).

[117] (Vol.2, p.332, 378, 382, 419).

[118] (Vol.2, p.448).

[119] (Vol.2, p.351, 420, 439, 321, 324, 327).

[120] (Vol.2, pp.282-3, 283-4, 285, 295).

[121] (Vol.2, p.448, 485, 488, 503, 254-8, 260).

[122] (Vol.2, p.483, 506, 515, 532).

[123] (Vol 16, pp.344-9, 392-413. Vol 17.p.53. Yoder, Unrolling time, 1988, p.84).

[124] (Vol.17, pp.88-91).

[125] (Vol.16, pp.384-7. Vol.11, pp.72-5, pp.320-1).

[126] (Galileo, Opere, Favaro, 1929-39. Vol.VII, pp.58-9. Vol.VIII, pp.107-120, 335-345. Huygens : Vol.16, p.385).

[127] (Vol.16, p.386, p.417).

[128] (Vol.16 pp.387-391).

[129] (Vol.16, pp.392-413).

[130] (Mahoney, Studies on Ch. Huygens, 1980, p.238. For further mathematical explanation see Mahoney, 1980, and Yoder, Unrolling time, 1988. Mahoney says that Huygens was initially inspired by Pascal's work of 1648, R.Taton, Dictionary of Scientific Biography, Vol.X).

[131] (Mahoney, 1980, p.242).

[132] (Vol.17, pp.88-9. For the calculations of the length of the cord of the conical pendulum see Yoder, 1988, p.29).

[133] (See design in Vol.17, p.90).

[134] (Yoder, 1988, p.31, 191).

[135] (Vol.17, p.97).

[136] (Vol.17, p.91; Vol.16, pp.307-8, 319).

[137] (Vol.16, p.392-97, for modern notation of Huygens' mathematical deduction of the cycloid, see Whiteside's The Mathematical Papers of I.Newton, 3,1969, p.393).

[138] (Vol.16, p.392).

[139] (Vol.16, p.393 and for all the derivation see in the same volume pp.393-413).

[140] (Galileo, Opere, Favaro edit.1929-1931. Vol.VIII, p.339).

[141] (Yoder, 1988, p.51).

[142] (Vol.16, p.398; Yoder, 1988, p.52).

[143] (Vol.16, p.394, Galileo's Discorsi, Proposition 1).

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[144] (Yoder, 1988, p.53).

[145] (Galileo, Opere, Favaro, 1929-1939, Vol.VII, p.253).

[146] ($\frac{\text{time through KA}}{\text{time through TZ}} = \frac{p}{q\sqrt{2}}$
"This is the ratio of one-fourth the circumference of a circle to its subtending cord ($\pi / 2\sqrt{2}$) z" Yoder, 1988, p.58).

[147] (Yoder, 1988, p.58).

[148] (Yoder, 1988, p.70).

[149] (Vol.17, p.97).

[150] ("horologemaecker vraegen van de secundenwijser door 't schaeckelradt te doen gaen om de gelijckheijt. Van het grootte radt grooter te maecken. Van 't schuijflootie te seggen", Vol.17, p.105).

[151] (Westfall R., Force in Newton's Physics 'Ch.Huygens Kinematics', 1971, pp.146-193).

[152] (Vol 16, p.255 and Westfall, 1971, p.167).

[153] (Vol 16, p.310).

[154] (Westfall, 1971, p.172).

[155] (Vol 16, 267-73, Westfall, 1971. For circular motion the formula would be: $F = mv^2/r = m\,r\,w^2$, p.170).

[156] (Westfall, 1971, p.171).

[157] (Vol.16, pp.278-9. Vol.17, pp.100-1; Huygens found the value of g in '*pieds rhénans* and in seconds :

$$g = \frac{4\pi^2 .123120000}{12.3600^2} = 31{,}25\ \frac{\textit{pied rhénan}}{\text{sec } 2}\ )$$

[158] (Vol.3, p.438).

[159] (Vol.4, p.27, 93).

[160] (Horologium, Pars Quarta, Prop.XXIV; for the centre of oscillation see: Vol.16, p.415-555).

[161]

$$(\quad G = \frac{4\pi^2 r^2 L}{3{,}600^2} \quad \text{or} \quad T = \pi\sqrt{L/g}$$

This formula gives the general value of g as a function of longitude and velocity for any pendulum we might use. Huygens used a short pendulum of 6,10 inches which swung 4,964 double oscillations per hour, and found a value that is being accepted since then:

g = 31.25 feet (=98 cm) Koyré, 1977,p.298-9).

[162] (Vol.2, p.181).

[163] (Vol.2, p.266; pp.304-5).

[164] (Vol.16, pp.414-433).

[165] (Vol.16, p.384 "Ergo sicut gravitas plumbi ad gravitatem ligni ita fit diameter sphaerae lignae ad diametrum sphaerae plumbae, aeque velociter atque illa decidet". Vol.3 p.425; Vol.4, p.35, 47, 60, 86-7 and 93).

[166] (Vol.17, pp.106-113. Vol.16, pp.415-498).

[167] (Vol.16, pp.498-541).

[168] (Vol.17, pp.102-5).

[169] (Vol.17, pp.120-153).

[170] (Vol.3, p.13; to Schooten, p.44; to Carcavy, p.57; to Hevelius, pp.134-5).

[171] (Vol.3, p.298).

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[172] (Vol.3, p.25).
[173] (Vol.17, pp.98-102).
[174] (Vol.16, pp.434-454; Vol.17, pp.149-152).
[175] (Vol.18, p.339).
[176] (Vol.18, p.341).
[177] (See for the whole deduction. Vol.18, pp.342-3).

[178] (*Horologium Oscillatorium*, Part IV, Prop.XXIII, pp.338-343. Huygens gave some examples on the length of the compound pendulum and how the speed of the pendulum would vary when the sliding weight was moved upwards in the verge, from pp.344-346. For more modern explanation of the compound pendulum, see in Studies of Ch.Huygens, 1980, Gabbey, pp.185-189, and Mahoney, pp.248-251).
[179] (Vol.18, p.304, Prop.XX; 348, Prop.XXIV).
[180] (Vol.18, pp.348-355).
[181] (The *pied horaire* was defined by Huygens as a foot determined by the length of the pendulum itself, Vol.18, p.95).
[182] (Vol.18, p.304).
[183] (Vol.18, pp.325-353).
[184] (Vol.18, pp.352-5).
[185] (Vol.5, p.375).
[186] (Vol.17, p.183, Fig.75 in OC).
[187] (Vol.6, p.171).
[188] (Volumes 16 and 17).
[189] (Vol.7, pp.487-490).
[190] (Vol.18, pp.74-81).
[191] (Vol.18, p.76).
[192] (Vol.7, p.258).
[193] (Vol.18, p.71).
[194] (Vol.18, p.76).
[195] (Vol.18, p.86-7).
[196] (Vol.18, pp.88-9).
[197] (Vol.18, pp.90-1).
[198] (Vol .18, p.71).
[199] (Vol.18, pp.92-6).
[200] (Vol.2, p.333).
[201] (Vol.2, p.522).
[202] (Vol.18, pp.98-102).

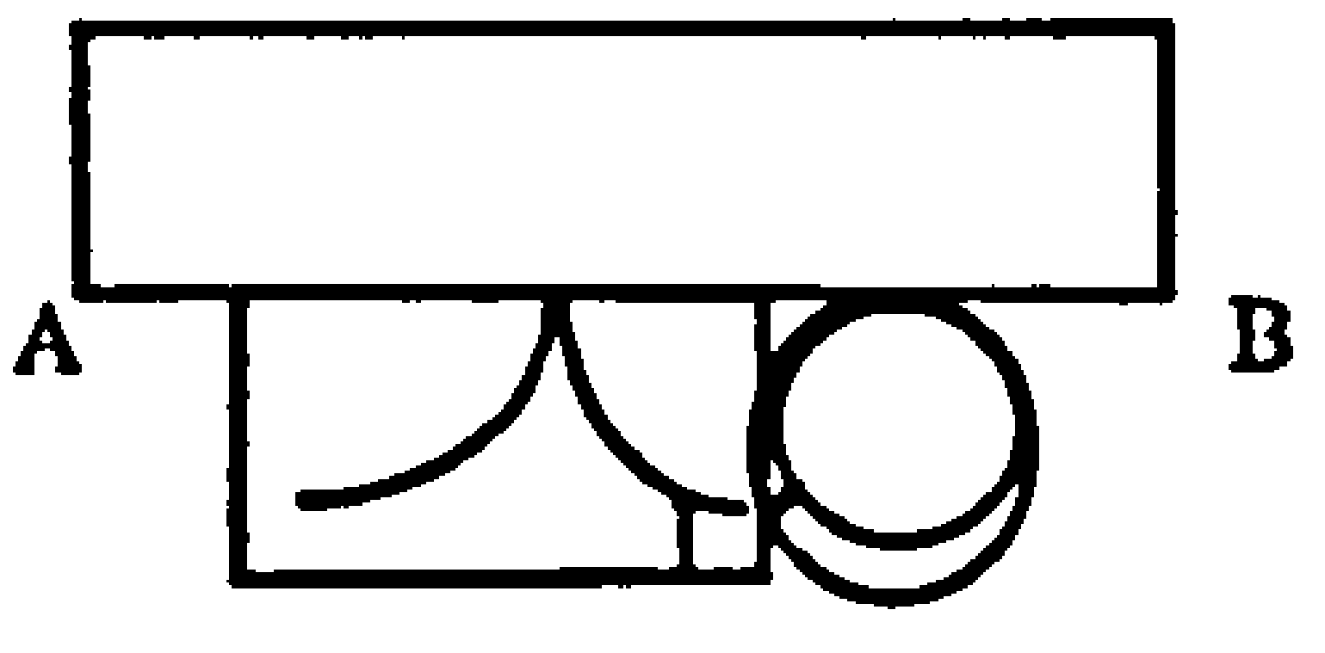

Figure 17. Drawing the cycloid.

[203] Vol.18, pp.102-3).
[204] (Vol.18, p.105).
[205] (Vol.18, pp.106-7).
[206] (Vol.18, pp.112-3).
[207] (Vol.18, pp.106-9).
[208] ("Hypothesis I: Without the action of gravity and air resistance, the movement of a body would be in a straight line. Hypothesis II: In free fall a body falls following a

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composed movement, one the uniform movement they would normally follow and the second due to the action of gravity. Hypothesis III: This hypothesis proves that one movement cannot happen without the other". Vol.18, pp.124-5).

[209] (For instance Proposition I: the velocity of fall increases at equal intervals of time and the differences between the spaces fallen on those times are constant. Vol.18, p.126-7. For the other 5 propositions, see pp.128-143).

[210] (Prop.7 Vol.18, pp.142-3).

[211] (Prop.8, Vol.18, pp.144-5, see also Pro.9, pp.146-7. " A body descending through inclined planes of a given height but with any inclination, will always acquire the same speed, will be equal to the free fall from the same height.

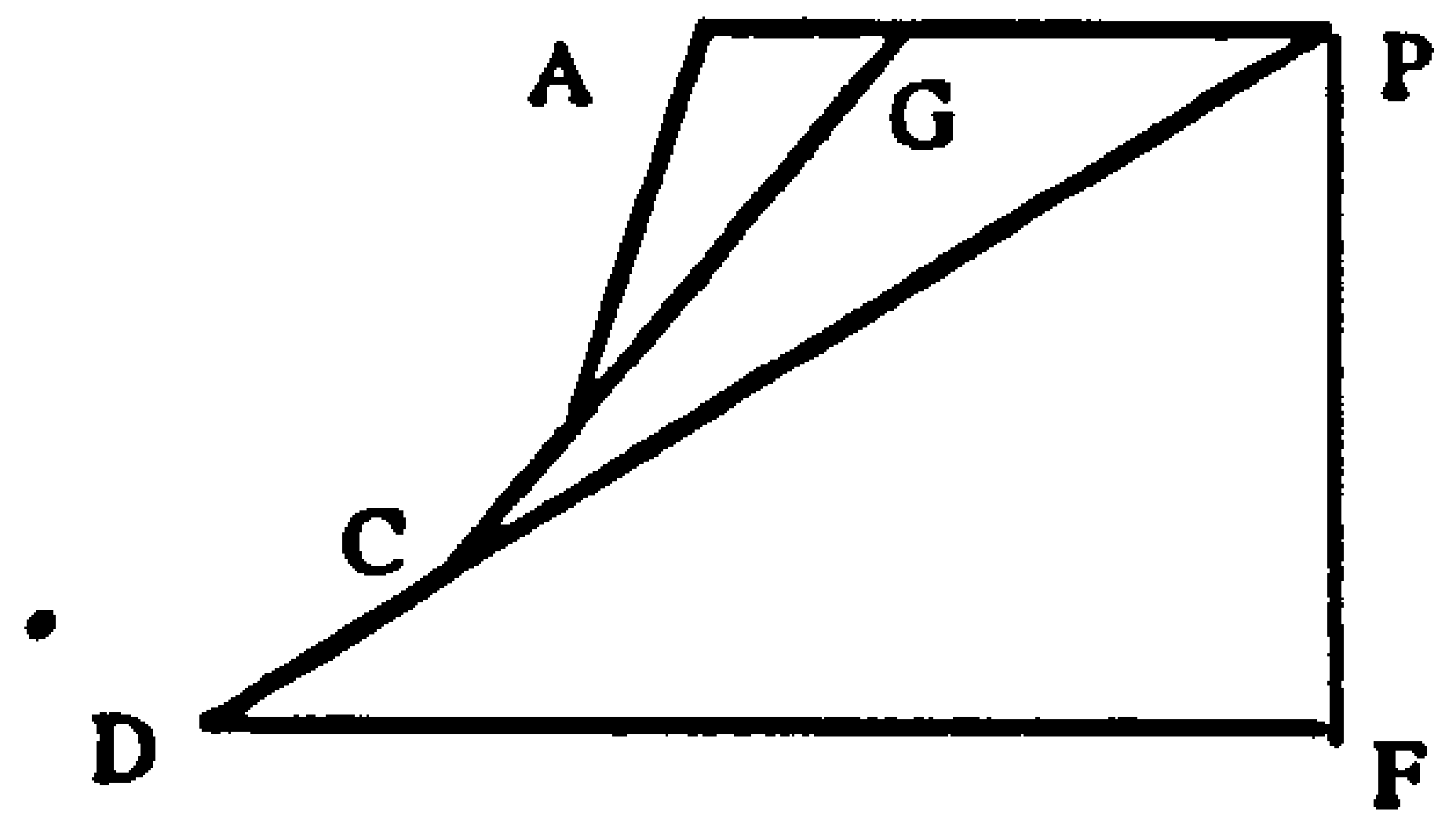

Figure 18. Fall of a body through inclined planes PD, GCD, ACD and free fall through PF).

[212] (Prop.14-15-16, Vol.18, pp.152-161).

[213] (Prop.10-11- 12, Vol.18, pp.148-151).

[214] (Prop.17-18, Vol.18, pp.160-3).

[215] (Prop.19-20, Vol.18,pp.162-5).

[216] (Prop.21-22, Vol.18, pp.164-9).

[217] (Prop. 23, Vol.18, pp.170-3).

[218] (Prop.24, Vol.18, pp.174-183. And further ratios between cycloids and the tangent to it, together with the circles, which form them, as well as their diameter, see Prop.25-6, pp.184-7).

[219] (Vol.2, p.518).

[220] (Vol.2, p.522).

[221] (Definitions I-IV, Vol.18, pp.188-9).

[222] (This curve described by the pendulum was called in the basic definitions, *développante* , Definition III, and the développée which is the Evolute, or developed from the cycloid giving the cheeks their form, Definition IV, Vol.18, pp.188-9).

[223] (Prop.VII-VIII, Vol.18, pp.202-7).

[224] (Prop.I-II-III-IV-V, Vol.18, pp.190-9).

[225] (Prop.VI, Vol.18, pp.200-1).

[226] (Prop.X-XI, Vol.18, pp.220-241).

[227] (Prop.IX, Vol.18, pp.208-221).

[228] (Vol.2, p.37, 40, 42, 44, 58, 105, 111, 156, 164, 353, 557).

[229] (Leonhardi Euleri, Opera Omnia. Edit. Ch.Blanc, Series Secunda. Vol.8, Commentationes mechanicae. De Motu Tautochrono Pendulorum Compositorum, 1750-1, pp.286-293 and on air resistance pp.294-306).

[230] (This formula Huygens deduced in 1669, Vol.6, p.488 $x = \sum r^2 / nb$, x= length of isochronous pendulum, or, $l = I/Mb$; l= length of isochronous pendulum, I = moment of inertia of the swinging body, M = mass of the body; b= distance of its centre of gravity to the axis of suspension. Vol.18, p.33. Prop.XIII, 1664, Vol.16, p.461; Prop.XVI, 1669, Vol.16, p.373).

[231] (Vol.18, p.53. Vol.1, pp.45-6, 50-1, 53).

[232] (Vol.1, p.45).

[233] (Vol.18, pp.57-8).

[234] (Vol.16, pp.457-460).

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[235] (Vol.1, p.23, 45; Vol.18, pp. 242-3).

[236] (Vol.2, p.557).

[237] (Vol.2, p.220).

[238] (Vol.16, pp.379-555. For editor's notes see in the same volume pp.331-378)

[239] (Vol.18, pp.242-3)

[240] (Definition I: "We call a pendulum, any figure with a weight, either a line, a surface, or a solid body, suspended in such a way that by the force of gravity, it can continue on a continuous movement around a point, or around an axis parallel to the horizon". Vol.18, pp.244-5).

[241] (Definition V, Vol.18, pp.244-5).

[242] (Definition IX, Vol.18, p.246-7).

[243] (Hypothesis I-II, Vol.18, pp.246-251).

[244] (Prop.I-III, Vol.18, pp.250-5).

[245] (Prop.IV-V-VI, Vol.18, pp.254-265).

[246] (A cylinder truncated by a 45° plane and created by the revolution of an inclined plane, another plane in the base and a line which kept perpendicular to the base plane as it evolved in a circle around both planes. Definition 14 and 15, Prop.VII-VIII, Vol.18, pp.264-269. Very small perpendicular prisms in small squares then divided the figure. Prop.IX-X, pp.270-5).

[247] (Prop.XI, Vol.18, p.274-5).

[248] (Prop.XII, Vol. 18, pp.274-281).

[249] (Prop.XIII, Vol.18, pp.280-3).

[250] (Prop.XIV, Vol. 18, pp.282-9).

[251] (Prop.XV, Vol.18, pp.288-295).

[252] (Vol.18, p.244-5. Vol.16, pp.361-373).

[253] (Prop.XVI, Vol.18, p.291-7; Vol.16 p.510-3).

[254] (Prop.XVII, Vol.18, p.296-299).

[255] (Vol.16, p.472, 474, 477, 508 and 551).

[256] (saying that "the space of a plan multiplied by the number of squares of the *particules* of the suspended figure, is equal to the addition of the squares of the distances to the axis of gravity, parallel to that of oscillation).

[257] (Prop.XVIII, Vol.18, pp.298-303).

[258] (Prop.XIX, Vol.18, p.302-5. Huygens said that the centre of oscillation and the point of suspension were reciprocal, Prop.XX, Vol.18, p.304-5).

[259] (Prop.XXI, Vol.18, p.304-311).

[260] (Vol.18, p.310-1).

[261] (Vol.18, p.310-1).

[262] (Vol.18, p.310-3).

[263] (Vol.18, pp.312-3).

[264] (Vol.18, pp.312-7).

[265] (Vol.18, p.316-7).

[266] (Vol.18, p.316-7).

[267] (Vol.18, p.316-9).

[268] (Vol.18, p.318-327).

[269] (Prop.XXII, Vol.18, pp.326-7, 326-331, 330-3, 333-4, 334-9).

[270] ("la longueur d'un pendule simple isochrone avec le pendule donné s'obtiendra donc en divisant la somme des carrés des distances de toutes les particules au point du suspension , par la somme de ces distances" Prop.XXIII, Vol.18, pp.338-347, with examples, pp.346-7. And further studies on the compound pendulum, Prop.XXIV, pp.346-9).

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[271] (*Pied Horaire*, defined by Huygens in Vol.18, p.96. Prop.XXV, Vol.18, pp.348-355).

[272] ("les longueurs de deux pendules quelconque son entre elles comme les carrés des temps dans lesquels se sont leurs oscillations; par conséquent ces longueurs sont inversement proportionnelles aux carrés des nombres des oscillations exécutées en des temps égaux" Vol.18, pp.352-5).

[273] ("Or, the very small simple pendulum do not differ a lot from the pendulum suspended between the cycloidal cheeks, having the same length", Vol.18, pp.354-5).

[274] (Prop.XXVI, Vol.18, pp.354-9).

[275] (Vol.18, pp.360-1).

[276] (Vol.18, p.363).

[277] (Vol.18, pp.362-5. For a circular clock to measure the demi-seconds it is necessary that the parabole EF be of 4 1/2 French inches of the horary foot seen above. For seconds this should four times that measure).

[278] (Theorem I: "lorsque deux mobiles égaux parcourent en des temps égaux des circonférences inégales, la force centrifuge correspondant à la plus grande circonférence sera à celle qui correspond à la plus petite dans un rapport égal à celui des circonférences elles mêmes ou de leurs diamètres". II: "deux mobiles égaux se meuvent avec la même vitesse dans des circonferences inégales, leurs forces centrifuges seront inversement proportionnelles sur diamètres". III: "deux mobiles égaux se meuvent dans des circonférences égales avec des vitesse inégales, la force centrifuge du plus rapide sera à celle du plus lent dans un rapport égal à celui des carrés des vitesses". ... Vol.18, pp.365-6)....

[279] (Theorem IX: Vol.18, pp.367-8 and Theorem XII: " two pendulums with the same weight, but different cord lengths, descrive when turning, conical surfaces and that the heights of the cones are equal, the force along the cord will be in a ratio equal to that of the length of their cords" Vol.18, pp.367-9).

[280] (Vol.18, pp.369-439).

[281] (On ratios of free fall and circular motion. Appendix II to Part I, 1659-1693-4, Vol.18, pp.374-387).

[282] (In Pars II: Prop.II-VI; IX, X and XXIV. Pars III: Prop.III. In Pars IV: Prop.IV-V, Vol.18, p.50).

[283] (Vol.16, p.303, figure, p.302; Vol.18, p.45).

[284] (Editor's comment, Vol.18, p.46).

[285] (M.S.Mahoney, Boss edit. Studies on Ch.Huygens, p.246).

[286] (Britten, Old Clocks and Watches, 9th edition, 1977, p.264).

[287] (Vol.2, p.266).

[288] (Vol. 4, p.54, 94, 264).

[289] ("car je croy fermement qu'il n'y a point d'autre methode pratiquable pour les longitudes que par des horloges justes" Vol.4, p.151).

[290] (Vol.17, p.97).

[291] (from Moray 1662, Vol.4, p.27; also clocks made by Thuret, who claimed they were his, Vol.4, p.270).

[292] (Vol.4, p.54. Mahoney, Studies on Ch.Huygens, 1980, p.247; Mahoney's: how to determine longitude: In 24 hours the earth turns 360° from west to east. In local time, for every hour's difference between two points, there exists a difference of 15° in longitude. A traveler can determine the longitudinal distance from a starting point, by comparing the time of the sun where he is to the time of the clock. But after a few days travel he has to correct the local time because he has accumulated some inequality of the solar day).

[293] (Vol.4, p.56-7).

[294] (to Moray,Vol. 4, p.60; Horologium Oscillatorum, Vol.18, p.112-3).

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[295] (Vol.3, p.284; Vol.4, p.87).
[296] (Vol.4, p.324).
[297] (Vol.4, p. 411, 418, 430, 434, 452, 456, 460, 477, 478).
[298] (Vol.4, p.12, 25, 63, 65, 430, 434, 451, 477).
[299] (Vol.17, p.164-5).
[300] (Vol.6, p.167, 276).
[301] (Vol.17, p.164).
[302] (Vol.17, p.164).
[303] (Vol.4, p.456, for two identical clocks built by Oosterwijck, p.274).
[304] (Vol.3, p.284; Vol.4, p.256, 278).
[305] (Vol.5, p.9, 108).
[306] (Vol.17, p.166).
[307] (Vol.17, p.188).
[308] (Vol.17, p.189).
[309] (Vol.17, p.168).
[310] (Vol. 5, p.152-56; p.166-7; for 15 years: p.167; for 20 years: p.155, 223).
[311] (Vol.5, p.140, 157).
[312] (Vol.17, p.171, 178).
[313] (For an extract of the English patent office of the 3rd of March 1664, then amplified to the improved model in March 3rd 1665, see Vol. 17, p.176).
[314] (Vol. 4, p.428, 453; Vol.5, p. 40, 77, 94, 108, 113, 137).
[315] (Vol.4, p.432).
[316] (to Moray, December 1663. Vol.4, p. 458).
[317] (Vol.5, p.126).
[318] (Vol.4, p.444).
[319] (the letters have not been found).
[320] (Vol.5, p.186, To Moray, Jan.1665).
[321] (Vol.5, pp. 254-7, 264, 279).
[322] (Vol.17, p.173).
[323] (Vol.5, p.108, 148).
[324] (Vol.17, p.183-7).
[325] (Vol.17, p.185).
[326] (Vol.5, p.256).
[327] (Vol.17, p.183-5).
[328] (Vol.5, p.244; one by Thuret: p.267; Vol.18, pp.18-9).
[329] (Vol.5, p.241; also observed by Prince Maurice, count of Nassau, p.243; p.244, 247).
[330] (Vol.5, p.248).
[331] (Vol.5, p.256).
[332] (Vol.5, p.260).
[333] (Vol.5, p.264).
[334] (Vol.5, p.267).
[335] (Vol.5, p.282).
[336] (Vol.5, p. 342).
[337] (Vol.9, p.57).
[338] (Vol.18, p.118-9).
[339] (4th March, 1656. Vol.1, p.318-9).
[340] (Vol.1, pp.320-1).

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[341] (Wright, M. Robert Hooke's Longitude Timekeeper, in Hunter & Schaffer edit. Robert Hooke. New studies, The Boydell Press, 1989, pp.63-118).

[342] (Vol.17, p.199-235).

[343] (Vol.4, p.446-451).

[344] (Vol.4, p.452).

[345] (Vol.4, p.431-2, 459, 474).

[346] (Vol.4, p.443).

[347] (Vol.5, p.153, 174).

[348] (Vol.17, p.195).

[349] (Vol.5, p.174).

[350] ("Kort Onderwijs. Aengaende het gebruyck der Horologien. Tot het vinden der Lenghten van Oost en West", Vol.17, p.199-200; Vol.5, p.187, 240, p.247; p.255. For a translation into English, Vol.6, p.439, 440, 444. English version, Vol.6, p.446-459). And for a translation into French Vol.5, p.277, 343, 355, 361).

[351] (Vol.4, p.443. Vol.18, pp.16-7).

[352] (Vol.5, p.204).

[353] (On the second trip also see: Vol.5, p.234, 245, 260. Birch, History of the Royal Society of London, Vol.2, p. 4, 5, 21, 23, 24, 26).

[354] (Vol.5, p.223).

[355] (Vol.5, p.272 "j'ay conferé avec des Pilotes et gens de mer touchant l'affaire des longitudes" p.277-8).

[356] (Vol.5, "Dans les conversations que j'ay eves a Amsterdam avec quelques uns de nos gens de mer j'ay veu avec admiration combien ils sont tardifs et difficiles pour admettre quelque chose de nouveau, bien que l'utilitè en soit evidente" p. 283).

[357] (Vol.17, p.204-5, table of equation of time: p.207. Vol.4, p.56-7. For further explanation on how to do this calibration see: Mahoney, 1980, p.247).

[358] (Vol.17, p.208-11).

[359] (Vol.17, p.216-7).

[360] (Vol.17, p.216-7).

[361] ("*ne sont pas avec la chainette en dedans*", Vol.6, p.167).

[362] (Vol.18, p.10, figure1, 2 in OC).

[363] (Vol.18, p.11, fig.3, not known what type of new clock fig.4, in OC, represents).

[364] (See before, in marine clocks in 1665 he experimented with clocks hanging in this fashion. Vol.18, p.12, fig.5 and 6 in OC).

[365] (Vol.18, p.12, fig.6 in OC).

[366] (Vol.18, p.21-2).

[367] (Vol.6, p.200, 218, 379; Vol.7, p.26).

[368] (Vol.6, p.379, 428, Lodewijk talks of recent changes in the clock, 1670, Vol.7, p.26; poor results from the Canadian trip of 1670: Vol.7, pp.54-5, 142).

[369] (Vol.18, p.23-4).

[370] (Vol.18, p.24).

[371] ("horloges à chaîne", Vol.17, p.234).

[372] ("remontoirs à poids moteurs", Vol.17, p.235, Editor's note).

[373] (Vol.5, p.86, 114).

[374] (Vol.17, p.168+. About their point of suspension, see Vol.18, p.120-123).

[375] (Vol.18, p.13). And suggestions for new changes (Vol.7, p.210).

[376] ("l'horloge marine à ressort moteur et à pendule triangular" Vol.18, p.12)

[377] (Vol.18, p.13-16).

[378] (Vol.18, p.120-2, 289. Vol.6, p.491).

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[379] (Vol.18, p.13, 14, 120-1. Huygens' 1665 marine clock had "deux ressorts, un sur l'axe mesme de la roue de rencontre" "et dans la deuxième sur l'axe de la roue suivante" Vol.5, p.525. Thuret's clock also of 1665, Vol.5, p.511, "le deuxième ressort était également engagé dans le tour intérieur de la roue qui meut celle de rencontre").

[380] (Vol.18, p.100-2, 108-111).

[381] (Vol.18, p.114-7).

[382] (Vol.18, p.84).

[383] (Mémoires de l'Académie des Sciences despuis 1666 jusqu'à 1699, Vol.7, p.64-8).

[384] (Vol.18, p.77).

[385] (Vol.17, p.66, Editor's note 2).

[386] (Vol.18, p.19-20. It had the same wheels as the one in the Horologium, p.71, except for wheel H and I that had 40 and 20 teeth intead of the 48 and 24. The bob was of 648 g. and the verge of 45 g. The bob of the pendulum of 1673, p.71, was of three 3 French pounds).

[387] (Vol.18, p.19).

[388] (1674, Viviani's admiration of Huygens' work Vol.8, p.9, p.471. Vol.10, p.292).

[389] (Appendix II to Part I, Vol.18, p.374-87, or 1678, Appendix III to Part III, p.39-405; 1691, Appendix IV to Part III, p.406-9; Appendix VI to Part IV, p.433-6).

[390] (Vol.18, p.441-456).

[391] (Vol.18, p.457-466).

[392] (Vol.8, p.353-5, 356-8).

[393] (Vol.8, p.359-361, 363, 364-5, 365-7, 368-370, 418-9. Catelan still kept to what he had said, Vol.8, p.372-373. And against Huygens' cycloidal motion, Vol.8, p.395-398 and on the balance).

[394] (Vol. 8, p.537-8. Vol.18, p.460-1, Pièce VII, Pièce X of 1686).

[395] (Vol.9, p.463).

[396] (Piece II, Vol.18, p.p.607-620).

[397] (Vol.18, two pieces: I (1673-4), p.489-495; II (1674-75), p.496-8).

[398] (Corollary to Prop.II, Theorem XVIII, Book I).

[399] (Vol.10, p.52, 2nd March, 1691).

[400] (March, 1691, Vol.10, p.23-71).

[401] (Vol.18, p.497).

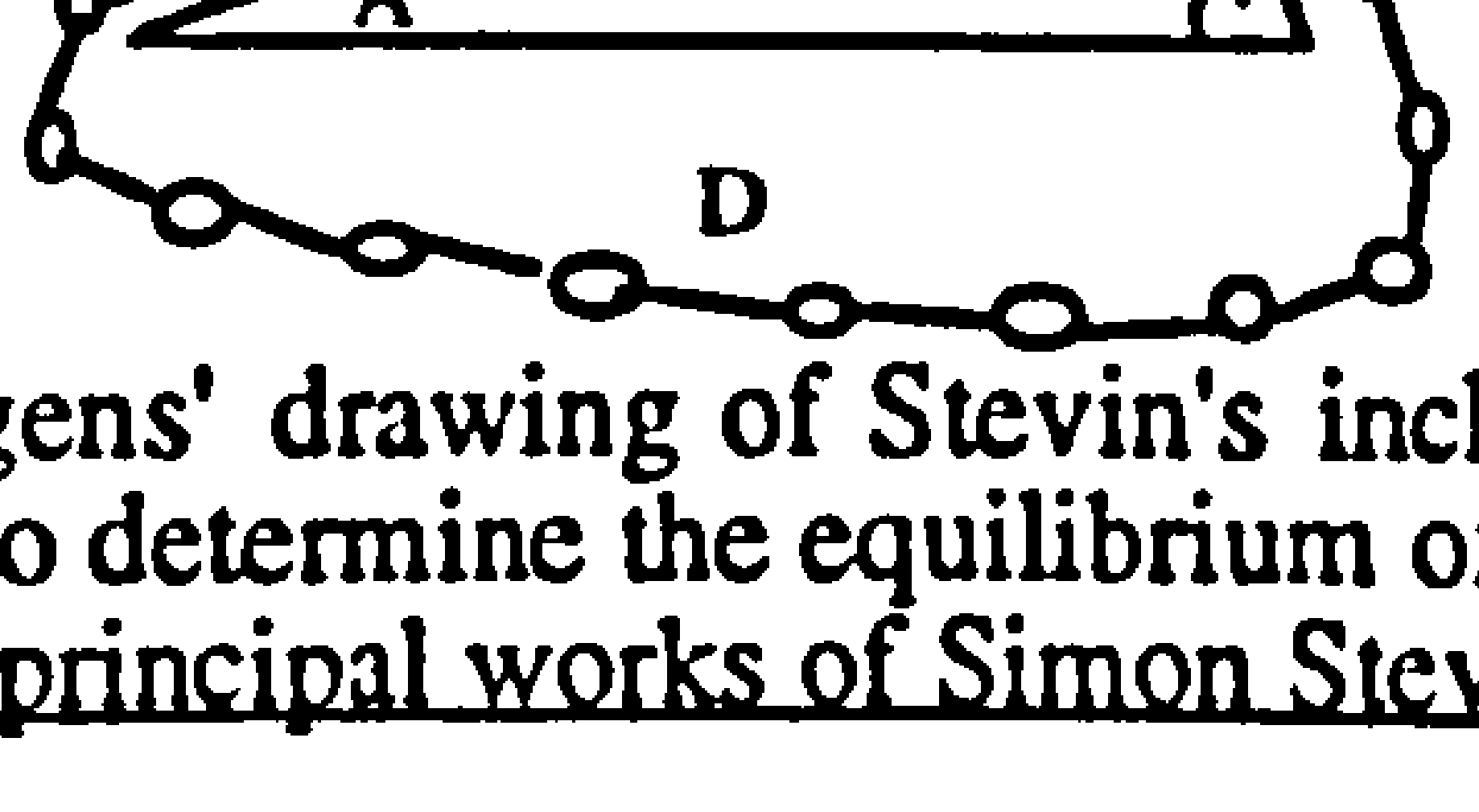
[402] (Vol.18, p.497).

[403] (Vol.18, p.497).

[404] (Vol.18, p.497).

[405] (Vol.18, p.498).

[406] (Vol.9, p.456).



[407] (Figure 27 - Huygens' drawing of Stevin's inclined planes ABC and two weights EF linked by a chain to determine the equilibrium of these weights. Vol.18, p.475-6).

[408] (Stevin S, The principal works of Simon Stevin, Amsterdam, 1966, Vol.5, pp.1-63).

[409] (Stevin S, The principal works of Simon Stevin, Amsterdam, 1966, Vol.1, pp.174+).

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[410] (Bacon R, J. H. Bridges edit, 1897, Vol.I pp.97-174; Opera hactenus inedita Rogeri Baconi, Mathematics, Facs.XVI, 1940, pp.73-155; Rogeri Baconis, Opus Minus, London, 1859, pp.313-389).

[411] ("In corporum motibus quibuscunque, nihil virium perditur aut interit nisi effectu edito et exstante ad quem producendum tantundem virium requiritur quantum est id quod decessit. Vires voco potentiam extollendi ponderis. Ita dupla vis est quae idem pondus duplo altius extollere potest". Vol.18, p.477).

[412] (Vol.10, p.382 from Leibniz).

[413] (End of 1692 and 1693 letters with Leibniz. Vol. 10, p.382, 384, 425).

[414] (- in briques et ressorts- Vol.17, p.270).

[415] (Duhem, Les origines de la statique. Paris, A.Hermann, 1905, I, p.57).

[416] (See the figure of a *ressort spirale* by Huygens, Vol.18, p.524 b).

[417] (Leopold, J.H. The Longitude Timekeepers of Christiaan Huygens, Proceedings of the Conference on Longitude, Harvard, 1996).

[418] (Vol.18, p.483. The Bernouilli brothers stated in 1691 that there exist an infinity number of curves different from the cycloid which produce isochronous oscillation. In 1693, Huygens said to Leibniz that perfect isochrony was obtained with the movement of the cycloid Vol.10, p.191).

[419] (Vol.7, p.424).

[420] (Vol.18, p.487).

[421] (Vol.7, p.519).

[422] (Vol.5, p.486).

[423] (Vol.7, p.449).

[424] (Vol.7, p.400, explained in p.422).

[425] (Berhoud F. 1976, p.138).

[426] (Britten's Old Clocks and Watches and their makers. London 1956, p.274).

[427] (Baillie, Watches, their history, Decoration, Mechanism, NAG Press Ltd, 1979, p.161).

[428] (Iliffe, R. In the warehouse: Privacy, property and priority in the early Royal Society. Hist. Sci., 1992, 30, pp. 29-68. It was Newton who stopped Hooke from any claims of priority when the latter wanted a place in the Principia because he also said to have inspired Newton with the notion of universal gravity: letter to Halley of June 20 1686. Westfall, R. Never at rest, C. U.P.1988, p.445).

[429] (Vol.7, p.407, 408-416).

[430] (Vol.7, p.422).

[431] (Vol.8, p.11).

[432] (Piece I, Vol.18, p.522-6. Vol.7, p408-9. In the Journal des Scavans, Vol.7, p.424-5).

[433] (Vol.7, p.474).

[434] (Vol.7, p.493).

[435] (Vol.7, p.509).

[436] (Vol.7, p.401, 416, 419-420).

[437] (Vol.18, p.523; Vol.7, p.411).

[438] (Vol.18, p.524; Vol.7, p.507).

[439] (Vol.7, p.408-9, 414).

[440] (Vol.7, p.425).

[441] (Vol.18, p.525).

[442] (Vol.7, p.409).

[443] (Vol.7, p.406).

[444] ("Monsieur Hook ne fait que ce que plusieurs horlogeurs d'icy on fait, qui est de varier la construction, ce qui n'est pas difficile" Vol.7, p.427, 499).

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[445] (André Thriry de Liége. Christiaan Huygens ses relations en Belgique. Horlogerie Ancienne, 1er Semester, 1995, p120).

[446] (Vol.7, p.427).

[447] (Vol.7, p. 433).

[448] (Vol.7, p.457; Vol.18, p.527).

[449] (Vol.7, p.401).

[450] (Piece II, Vol.18, pp.527-535).

[451] (Piece I, Vol.18, p.605. The anchor escapement functioned as follows: “when a tooth of the scape-wheel scapes from the pallet on one end of the anchor, a tooth on the other side engages with the pallet at the opposite end of the anchor” (Tait, Hugh, Clocks and Watches, British Museum, 1983, p.53).

[452] (Vol.18, pp.605-6, editor's note 1).

[453] (Vol.18, pp.65-6).

[454] (Vol.18, pp.621-2).

[455] (Vol.18, p.525 and in 1682 and 1684 p.526).

[456] (Vol.8, p. 429).

[457] (Vol.8, p.453).

[458] (Vol.18, p.532).

[459] (Vol.17, p.88).

[460] (Vol.18 pp.536-7).

[461] ("les forces de ces pesanteurs croissent en baissant ou haussant le dit corps, en mesme raison que celles d'un ressort comprimè, c'est a dire en raison des enforcements ou elevations" Vol.18, p.537).

[462] (Piece III, Vol.18, p.538).

[463] (Vol.18, p.548, 553, 555, 557, 561).

[464] (Vol.18, pp.548-9).

[465] (Vol.18, p.549).

[466] (Vol.18, p.550 drawing in 551).

[467] (Vol.18, p.552).

[468] ("Quarrez d'egal poids et egales distances, un quarrè de fer entredeux les sera egales en les attachant attachee en bas. Chaine de double quarrez tenants ensemble par un cost`e. percez quarrement, et avec deux rubans. serrez entre deux. Epingles à costé. Peu de distance entre ces chainons. Leur matiere d'estain assez mince. Cette chaine ne braflera pas comme la continue", Vol.18, p.555).

[469] (Vol.18, p.556).

[470] (Vol.18, p.556).

[471] (Vol.18, p.561).

[472] (Vol.18, p.532).

[473] (Vol.18, p.533).

[474] (Vol.18, pp.533-4).

[475] (September, Hudde wrote to Huygens, Vol.18, pp.534-5; Vol.9, pp.24-32).

[476] (Vol.9, p.31, 37).

[477] (Vol.18, p.539).

[478] (Vol.18, p.540).

[479] (Vol.18, pp.539-543).

[480] (to Thomas Helder, Vol.9, pp.55-76).

[481] (Vol.8, pp.342-3, p.393).

[482] (Vol.18, p.15).

[483] (July, Vol.8, pp.429-430. Oct. p.394).

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[484] (Vol.18, pp.527-545).

[485] (First trip: Vol.9, pp.277-291, 418-9).

[486] (Vol.9, p.467, 528).

[487] (Vol.10, pp.422-4, 513-5).

[488] (Piece VI, Vol.18, pp.562-570).

[489] (Vol.18, p.539, p.549).

[490] (Vol.18, p.549, 569).

[491] (Vol.18, p.549).

[492] (Piece VI. Vol.18, p.562, 567, 569. Piece VII, p.572, 590-1).

[493] (Piece VIII, Vol.18, p.596).

[494] (Vol.10, p.709).

[495] (Piece VIII, Vol. 18, pp.593-6).

[496] (Piece VIII, Vol.18, p.593).

[497] (Vol.18, p.538).

[498] (Vol.9, pp.55-76).

[499] (Vol.18, pp.643-652).

[500] (Vol.16, pp.30-91. Seven appendixes pp.92-168, from 1652-1675).

[501] (He wrote this in the last years of his life. "Manuscripts ultérieurs concernant l'historique de la doctrine du choc des corps et la question de l'existence et de la perceptibilité du mouvement absolu").

[502] (Some examples: Vol.18, pp.607-620, 621-2, 624).

[503] (Vol.18, p.563, 569).

[504] (Vol.18, pp.583-9).

[505] (De motu corporum and De Vi Centrifuga Vol.16).

[506] (Vol.18, p.554 "In corporum motibus quibuscunque, nihil virium perditur aut interit nisi effectu edito et extante ad quem producendum tantundem virium requiritur quantum est id quod decessit. Vires voco potentiam extollendi ponderis. Ita dupla vis est quae idem pondus duplo altius extollere potest").

[507] (Vol.18, p.668).

[508] (Vol.18, p.668).

[509] (Leopold, J. Clockmaking in Britain and The Netherlands. Notes Rec. R.Soc. London 1989, 43, pp.155-165).

[510] (Baillie, G.H. Watchmaker and Clockmakers of the World. N.A.G. Press Ltd. London, 1976, p.67).

[511] ("Patent conferred to Salomon Coster to be allowed for the time of 21 years alone here in this country to make and practice a certain new invention of Horology", Vol.2, p.237).

[512] ("we have received the humble petition that was presented to us by Salomon Coster stating how that petition Mr Huygens put into the petitioner's hands to dispose to his own advantage" Vol.2, p.237)

[513] (" a certain new invention of the clock, consisting of a movement greatly different from the one which has used until now,...and far surpassing the same in the precise measure of time", Vol.2, p.237).

[514] ("That is why it is no subject to noticeable alteration, neither to changes of weather or through faults of clockwork, that not only the public clocks through the application of the same gain in accuracy, but also in Astronomy and elsewhere, great benefit is expected", Vol.2, p.237).

[515] ("Nobody without his or the inventor's knowledge and permission, should be able to copy the same Horology after and charge for it". And later, " forbidding in this respect all and each inhabitant of the above mentioned United Netherlands & associated

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lands and members within the above mentioned time of 21 coming years, the written new invention of the Horologie, the whole or the part, the great or the small to copy, practice or having been copied it elsewhere to bring it into the country to sell within the country", Vol.2, p.237)

[516] ("on penalty of confiscation of all the imitated works and, moreover, of a sum of 300 Dutch florins", Vol.2, p.237).

[517] ("We consent, agree and patentize provided that he alone and excluding everyone else for the time of the 21 years". "The above mentioned new invention of the Horologie shall be allowed to make, practice and set it working and to have it done, practice and set it work, also promote and sell", Vol.2, p.237).

[518] ("We summon and command all officers, judges, magistrates and inhabitants of the described land together with all others it may concern that they permit & allow the above mentioned petitioner to enjoy and use the full effect of this patent, consent & privilege, ceasing all obstruction or argument to the contrary", Vol.2 p.237).

[519] ("we have received the humble petition that was presented to us in the name of Master Simon Douw, city clockmaker in Rotterdam, ... to make correct and well going Horology, and the same perfection has not been invented, because of this he the Petitioner, and master in the construction of big Tower Clocks and clocks for rooms"..."having by expertise and labour finally invented a certain new invention in Horology which was moved by an instrument, which was never before known in any branch of Mathematics or in the world" Vol.2, p.240)

[520] ("which in precise measurement of time, and also indurability gives less trouble", Vol.2, p.241).

[521] ("it is not subject to alteration neither by the small fit of the wheel-work nor for change of weather, nor by additional weight (in spite of the 10, 20, 30, 40, 50 or 60 weights added in proportion to the particular work) so that by the application of the petitioner's art above mentioned public works will acquire very great certainty generally and by which in course of time even greater advantage can be hoped for", Vol.2, p.241).

[522] (Vol.2, the States General to Douw, pp.240-242; Douw to the States General, pp.243-4).

[523] (Vol.2, p. 251).

[524] (Vol.2, pp.243-4).

[525] (Vol.2, p. 235).

[526] (Vol.2, pp.247-8).

[527] ("he has come first to beg to Coster and me, that we should also allow to pass his invention under our patent, and that he could also have permit to participate", Vol.2, pp.247-8).

[528] ("he managed with lies and tricks to achieve a patent from the States General", Vol.2, pp.247-8).

[529] ("it is very unreasonable that having produced something good I should have so much trouble and brain-racking and all that from such a scoundrel", Vol.2, pp.247-8).

[530] ("he will come and ... bring you and example of the description of these clocks on my behalf, which I have issued. If any tower clocks are mentioned to be made or changed according to the new invention I want him to be employed rather than any one working for Douw" Vol.2, pp.247-8).

[531] (Vol.2, pp.247-8).

[532] (Vol.2, p.251).

[533] (Vol.2, p.291).

[534] (Vol.2, p.183).

[535] (Vol.2, p.185).

[536] (Plomp, 1979, p.23).

[537] (Plomp, 1979, p.23+).

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[538] (Vol.4, p.411, 424, 434, 460, 477; Vol.5, p.103).

[539] (Vol.4, p.12, 65, 71; Vol.5, p.42, 47).

[540] (Editor's note, Vol.17, p.159).

[541] (Vol.2, p.209).

[542] (Brugmans H.L. Le Séjour de Christiaan Huygens, Paris, 1935, pp. 119-171).

[543] (Vol.2, p.456).

[544] (Moray to Huygens, Vol.5, p.114, Huygens to Moray p.119).

[545] (Vol.5, p.371, 511).

[546] ("*de remontage d'heure en heure*" Vol.5, p.525).

[547] (Vol.5, p.267).

[548] (Vol.5, p.357-8).

[549] (Vol.5, p.371).

[550] (Vol.5, p.511).

[551] (Vol.5, p.439).

[552] (Vol.5, p.474).

[553] (Vol.5, p.476).

[554] (Vol.5, pp.510-1).

[555] (Vol.17, p.82, note 4).

[556] (Vol.7, p.408, 412, 421, 435, 484).

[557] (Vol.7, p.408, 412, 421).

[558] (August 1675, Vol.7, p.484).

[559] (Vol.7, p.415, 435).

[560] (Vol.7, p. 498).

[561] (Vol.7, p.406).

[562] (Vol.7, p.542).

[563] (Vol.8, p.11).

[564] (Vol.5, p.491).

[565] (Piece VIII, Vol.18, pp.592-6).

[566] ("All in all one feels that there always is a great distance between Huygens and his clockmakers, and that he consistently underrated the part played, and the difficulties encountered, by his clockmakers" and later "it would be futile to criticize such a man simply because he did not get along very well with his clockmakers (Boss edit. Studies on Christiaan Huygens, 1980, p.224, 231).

[567] ("The majority of Hague clocks made in Amsterdam after 1685 had also both trains driven from one barrel" Plomp, Spring-driven Dutch pendulum clocks 1657-1710, 1979, p.153).

[568] (A three feet clock for Moray, Vol.4, p.87).

[569] (Daumas, 1972, p.28).

[570] (Leopold, 1980).

[571] (Vol.17, p.287, 290-1).

[572] (Vol.17, pp.288-9, 292-300).

[573] (Vol.17, pp.301-4).

[574] (Vol.2, p.281).

[575] (Vol.2, p.281, 286).

[576] (Vol.2, p.313, 331).

[577] (Vol.7, p.401).

[578] (Vol.7, p.419).

[579] (Vol.18, p.523; Vol.7, p.411).

[580] (Vol.7, p.507-8).

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[581] (Vol.21, pp.25-8, 43-6).

[582] (Vol.21, pp.28-30, 48-52).

[583] (Gooding edit. The Uses of Experiment, C.U.P.1989, p.41)

[584] (Gooding, C.U.P. 1989, p.82).

[585] (Gooding, 1989, p.90).

[586] (Vol.17, p.66).

[587] (Gooding, 1989, p.161).

[588] (Gooding, 1989, p.161-2).

[589] (Gooding, 1989, p.215-6).

[590] (Shapin, S. Closure and Credibility in 17th Century Science. Proceedings of the Manchester conference, 1988, pp.147-154.Gooding, 1989. Shapin, The House of Experiment in Seventeenth-century England, ISIS, 1988. pp.373-404).

[591] (Vol.2, p.253. And he also maintained correspondence with contemporaries he met in his trip to France in 1661: Brugmans, Paris, 1935, pp.119-177).

[592] (Schaffer, S. Scientific discoveries and the end of natural philosophy, Social studies of science, 1986, Vol.16, pp.387-420).

[593] (Bell, A.E. Christiaan Huygens, and the development of science in the seventeenth century, London, 1947).

[594] (Jones, R.V. Instruments & Experiences. 'Some considerations in Instruments design, 1988, pp.373-394).

[595] (Britten defines circular error as: "the time occupied by the swing of a pendulum varies as the square root of the length of its arc". F.J.Britten. Old Clocks and Watches, 9th edition, 1982, p.74).

[596] (Vol.4, p.432).

[597] (Vol.5, p.223).

[598] (Koyré, A. Del mundo cerrado al universo infinito. Estudios de Historia del Pensamiento Científico, Siglo XXI, 1977, pp.295-8).

[599] (Vol.18, pp.88-9).

CHAPTER 2

HUYGENS' AIR-PUMP WITH A PHILOSOPHICAL TWIST

Huygens' studies on the air-pump involved the creation of the best working instrument as well as performing experiments with it. Once the standard experiments had been defined and because of the difficulty of explaining them completely, Huygens tried to deduce a new theory of 'physics' as a basis to establish the instrument's performance. The work on the air-pump in the seventeenth century can be divided onto three stages: (a) the initial interest to prove the existence of a vacuum, a philosophical argument; (b) the emphasis put on experimentation and demonstration, an empirical phase; (c) the realization, especially by Huygens, that a good working instrument was essential to replicate the experiments, which can be defined as the engineering-design stage.

Huygens designed and built an air-pump after his trip to London (spring 1661), when he attended Boyle's meetings at Gresham College. There he learned that the aim of building a pump was to make its receiver airless. Boyle showed how the air-pump worked. Huygens was very impressed. He followed Boyle's instructions to create an air-pump and tried experiments with it. However, it did not work and Huygens decided to make his own pump, based on the designs for the compression of air of 1658[1], and on Boyle's model. I will be adding some details giving a Huyguenian perspective to the work by Shapin and Schaffer, who had dealt with calibration on the air-pump[2].

From the beginning, Huygens set out to improve the vacuum and to empty the receiver of air. As soon as his own pump worked he carried out several experiments with small birds or bells and alarm clocks to test the sound, and with small bladders and different materials (water, wine, mercury). All this convinced Huygens that the receiver could be made airless. However, the crucial experiment was the void within the void or Torricelli's tubes, which Huygens performed from 1661 until 1672. He used water drained or purged of air, fresh, or hot –a method used to treat water and other fluids but not described by Huygens. The phenomena observed encouraged him to develop a theory to decipher them. For seven years he observed the different bubbles which appeared in the tubes in the experiment of the void within a void. At that time, he believed water contained another matter. He doubted if something else remained in the receiver after emptying it of air. If that was the case, it had to be a matter made up of smaller particles than air. This matter could traverse glass and would still remain inside the airless receiver. This he deduced in 1668. His studies on matter of 1672 show that he believed in a subtle matter which filled the whole universe permeating everything, glass, water, air, mercury and any other elements. Certain experiments became standard, such as the void within the void, to check the precision and accuracy of air-pumps.

A new set of air-pump designs was elaborated in 1672. This time Papin participated and shared in the fruits of their common work. As with Coster and the pendulum clock, the right to publish the experiments and designs on the air-pump were passed on to Papin. By this time Huygens had invested a great amount of time thinking, designing and experimenting with the pump. From 1674 onward Papin continued experimenting according to Huygens' advice, and also introduced new designs for the instrument.

By the early 1670s the studies on pressure had begun and Boyle had published several treatises on the subject. Huygens received accounts of these publications from Oldenburg, secretary to the Royal Society in London[3]. Physical properties were studied of different elements: air, water, mercury and fire. During this time Huygens wrote[4] to Gallois about an invented barometer. It had developed from his studies on pressure derived from experimenting with the air-pump and from the physical studies on the properties of air, water and mercury. By 1686 Huygens developed his theory further in La Cause de la Pesanteur. Huygens' matter theory and his studies on statics and dynamics are presented in chapter 3. How did the air-pump come about?

1. THE ORIGINS OF THE AIR-PUMP

The air-pump came into existence, amongst other things, to prove the Aristotelian concept wrong. The Greek philosopher did not believe in the existence of a vacuum but Scholastics in the Middle Ages started to question the concept of space: was there something between the surface of a body and the space where that body was located? If so, it had to be filled, but with what? The reappearance during the Renaissance of classical thought in the translations of Greek philosophers' work raised more questions than answers to the concept of space and the explanation of the physical world. Moreover, the technological tradition began by the crafts, -e.g. Leonardo da Vinci and Galileo- opened new possibilities for the development of science and technology. Natural experimenters of the seventeenth century studied these questions trying to explain the laws of nature and the way the universe worked.

One Greek author was pivotal in this period. As Pacey points out, Hero of Alexandria influenced G.B.della Porta (1535-1615) who wrote a book on natural magic and later three on pneumatics[5]. From then on the void became an important concept and could be proved by making a container airless to create a vacuum. They began with Torricelli's experiments consisting of inverted tubes filled with either mercury or water.

The air-pump was also influenced by the technological work on water-pumps[6]. In the early 1650s, Otto Von Guericke invented the air-pump while pumping water out of an airtight copper vessel (figure 1). Air was made up of corpuscles acting like a fluid; the vessel could be emptied of air[7]. These were the Magdeburg experiments, accompanied by studies on the weight and pressure of air[8]. In 1657, Caspar Schott published Von Guericke's experiments in hydraulics and pneumatics. Robert Boyle read the book and arranged for Hooke to build an air-pump like Von Guericke's (figure 2)[9]. Galileo in his <u>Discorsi</u> showed that inverted tubes of water could be used to measure atmospheric pressure. Following these theories Torricelli connected several inverted tubes and experimented with mercury as well as with water.

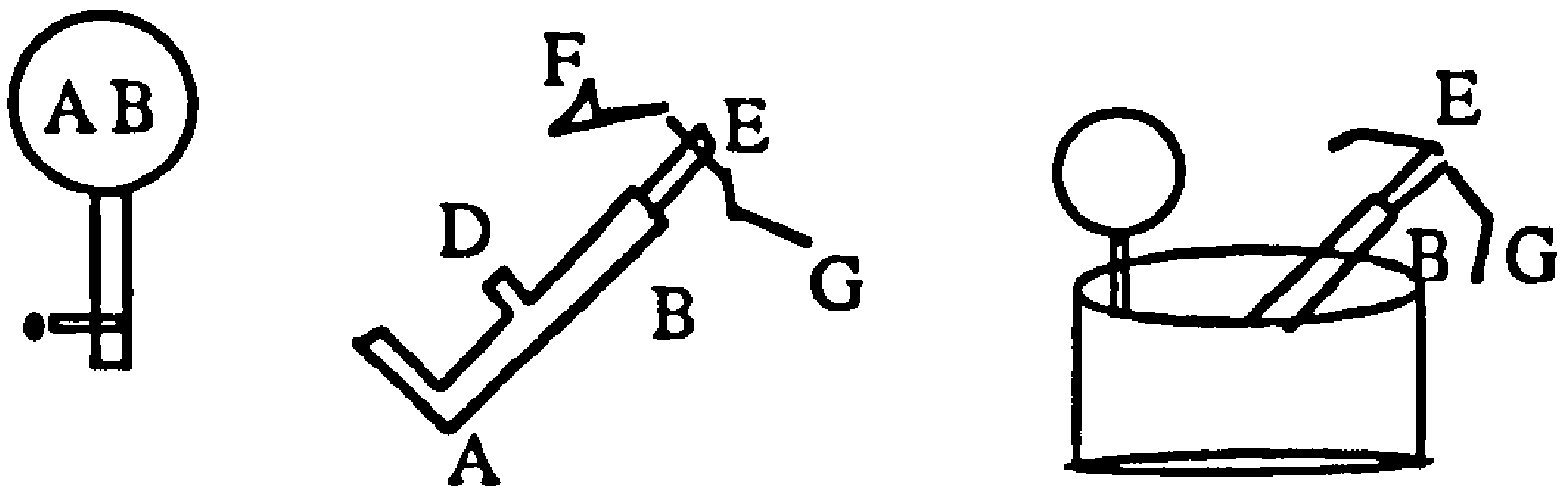


Figure 1 - Von Guericke's air-pump, from Schott, <u>Mechanica Hydraulico-Pneumatica</u> (1657), plate LVI.

In figure 1, AB was the receiver and ADB the cylinder with valves at A and D. E was the pump and FG the leather thongs used to pump air out of the cylinder. The pump was placed in a barrel of water to make it airtight[10].

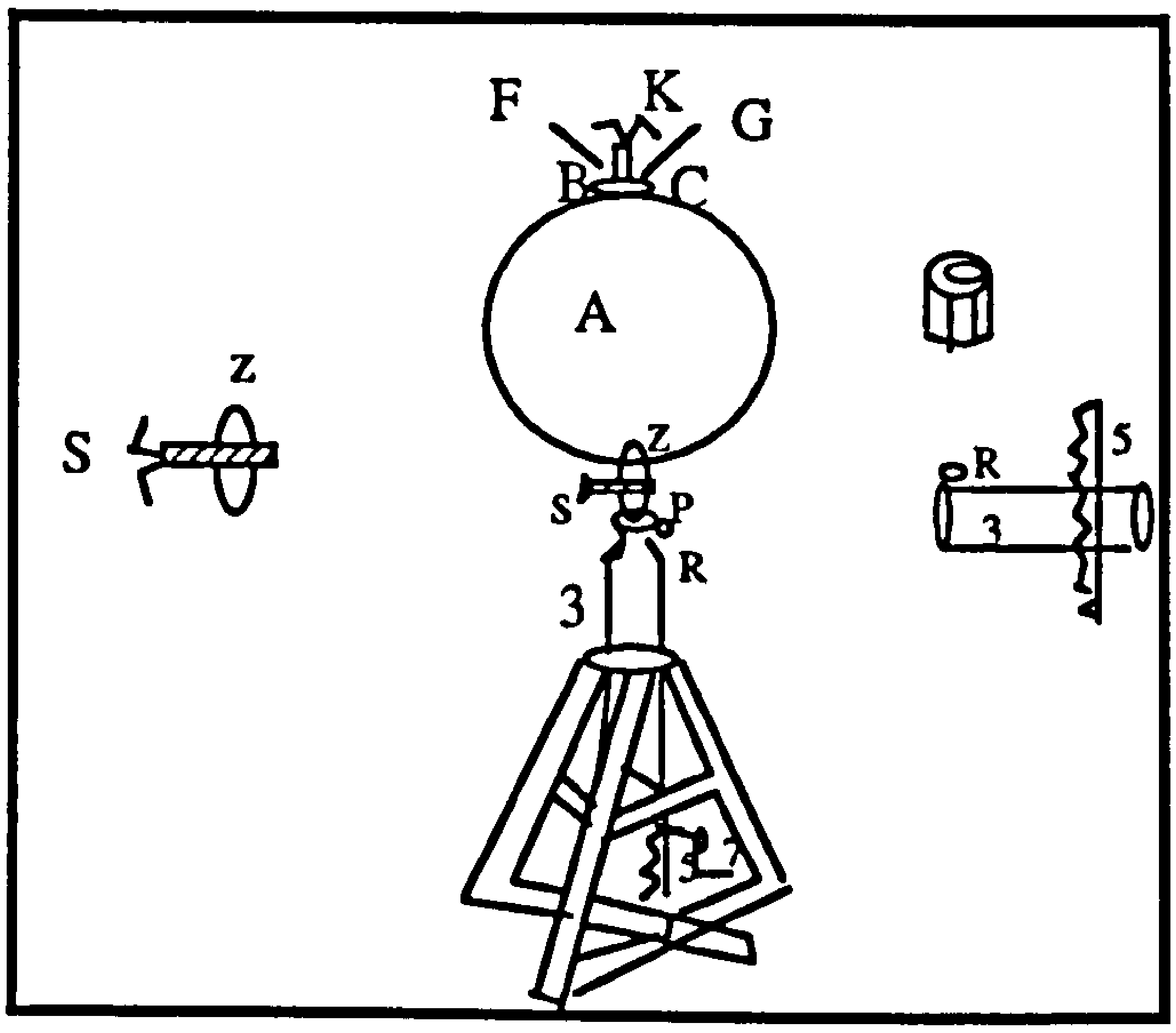


Figure 2 - Boyle's first air-pump, designed by Hooke, from Boyle, New Experiments Physico-Mechanical (1660).

In Boyle's model, the receiver, A had a capacity of 30 wine quarts; BC was the metal cap on the receiver. FG was a removable top, K, and S, the stopcock, between the receiver and the pump; O was the shank connecting them. Z was the opening of the shank into the receiver. The cylinder of cast brass (3) was 14 inches long with a bored center of 3 inches in diameter. P was the neck of the cylinder, into which the stopcock fitted. R was the valve, a tapering peg of brass fitted into the cylinder; 7 was the piston and 5 the rack[11].

Torricelli's experiments were often used as a reference. Experimenters of the air-pump did so at Gresham College, later at the Royal Society, in London, and in Paris, at Montmor's academy later the Académie des Sciences[12]. Mersenne (1588-1648) believed that vacuum existed in the pores of natural elements such as air and water. He saw Torricelli's experiment in 1649 on his visit to Rome[13]. I. Beeckman (1588-1637) believed in the possible existence of this vacuum when he wrote to Mersenne in October 1629[14]. According to Torricelli when a tube of mercury was turned upside down over a plate with some mercury in it, the column of mercury descended in the tube leaving an empty space behind. He concluded that the empty space might be the vacuum[15]. In 1644, Torricelli reported the variation of the weight of the column of air. He was the first to say that an instrument could be made to show that variation, and he clearly saw a difference between elasticity of air and its weight[16]. Blaise Pascal (1623-1662) proved that the same height was maintained whatever the height or form of the vertical glass above the column of mercury (figure 3a). Although he was not interested in the pressure of air, he designed what would become a key experiment for natural experimenters: the vacuum in a vacuum using a bent glass (figure 3b).

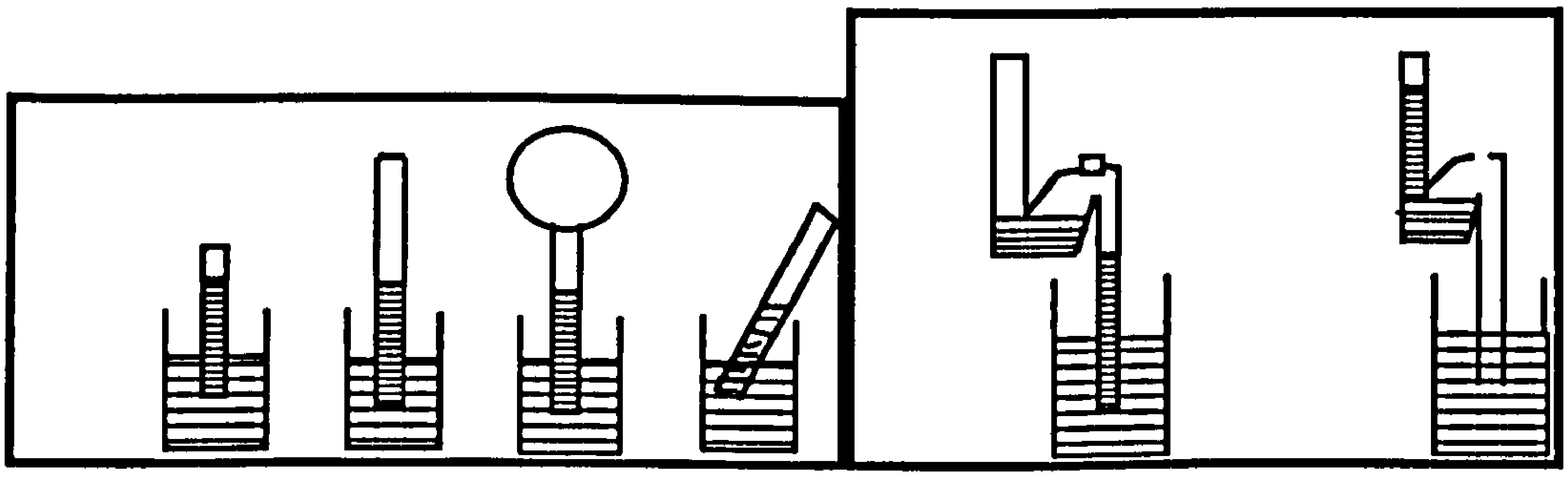


Figure 3 a, b - Pascal's vacuum in a vacuum[17].

When the apparatus was filled with mercury, the lower leg worked as a barometer, but the mercury in the upper tube stood no higher than the reservoir. A hole was opened at the top of the leg (second column in figure 3b) and as the air filled the tube, the mercury decreased slowly reaching the same level as the dish as it rose in the top tube at the same time[18]. He related the height in the column of mercury to atmospheric pressure[19]. After Pascal, the barometer functioned as a simple mechanical balance. Boyle (1627-1691) was the first to use the word barometer and Oldenburg suggested its regular use when referring to the Torricellian experiment[20].

Wren suggested to Boyle to fill a tube with mercury[21]. Boyle developed the Torricellian experiments further and placed Torricellian tubes inside the receiver of a pump. The weight of the air, the atmosphere, had to exert a pressure upon the column of mercury. Only the weight of the atmosphere determined the height of a given fluid. It was then possible to measure atmospheric pressure with a barometer. The barometer became a useful instrument for natural philosophers to debate metaphysical concepts. It provided them with a quantitative factor for experimental investigation.

Roberval found that by heating the top of the tube the column of mercury descended and that by letting some air in, it was depressed further. Longer tubes created a bigger space occupied by the vacuum making the volume of air less effective[22]. It was this pressure that kept the column of mercury up. It was not only the demonstration of the existence of the vacuum, but also studies about air, pressure, dilatation and compression that developed from the research with the air-pump.

After 1662, Huygens also carried out experiments on the pressure of air outside a tube and on its compression inside a tube.

Boyle's experiments were fully documented and anybody could replicate them. Huygens shared Boyle's concept of air being an elastic fluid that expanded when the external constraint was removed. With the air-pump it was possible to vary the pressure and to create a vacuum in the laboratory itself[23]. The attention was drifting from proving the existence of the void to explaining the phenomena found in it. According to Helden (1991), Boyle made this change. I would add that Huygens also played an important role in this. He was trying to find an interpretation of the observed phenomena produced by a new instrument that is why he continued his studies on matter theory for more than ten years (see chapter 3 below).

2. HUYGENS' DESIGNS OF THE AIR-PUMP AND EXPERIMENTS. THE BAROMETER.

Huygens knew about Pascal's experiments already in 1646 and 1647 through Mersenne's correspondence[24] and, later on, in 1654, through Moray[25]. In 1648 Huygens got to know about the Torricellian void through Mersenne's letters to his father, Constantijn[26], and to Christiaan[27] who wrote back suggesting that the swollen bladder observed in the vacuum was caused by the dilatation or rarefaction of the air contained there. In 1648 Christiaan was already referring to small, hard and spherical atoms filling the space of the void. Democritus' atomic theory influenced him in his work on the air-pump and on his deduction of matter theory. What was different was that Democritus believed in absolute void, but did Huygens? He saw the making of an airless receiver as a purely physical property of air. However, his work shows the existence of yet another apart from air in the receiver.

Thevenot sent Huygens news on the experiments carried out on the vacuum at the Accademia del Cimento in 1660[28] and a year later Ricci did the same[29]. However, it was only when he saw how Boyle's air-pump worked in London[30] that he decided to make one himself and carry out the corresponding trials; Boileau wanted to be kept informed about them[31]. To his brother Lodewijk he wrote about "those beautiful experiments on the vacuum" just by using "a certain pump from which all air was emptied from a big glass and where an animal or something else was placed"[32]. On his way back to The Hague, Huygens attended scientific meetings held at Montmor's house, where they started to define the origins of the rules of the future Académie des Sciences[33]. Moray sent his best wishes so that it would search for "the truth of things by truthful means"[34]. Huygens' intention to build his own air-pump when he came back to The Hague was known to Moray and Boyle by October 1661[35] they waited for news about his results. In a letter, Moray had said that they would not make improvements to Boyle's air-pump until Huygens had built and tried his own. Changes would be made according to the outcome of Huygens' experiments[36]. Huygens made his first design in November[37]. A month later he performed several trials, the most challenging of them was the void within the void. This shows once more the trust and appreciation those colleagues had for his work, thereby giving him authority in many debates about new observed phenomena.

Huygens' designs (as with the pendulum clock of 1656), showed new developments of the pump. As an engineer he tried to improve every small part of the instrument. First he made the drawings, and then he tried the instrument and observed what had to be changed. These changes were applied to the pump and tested. The results observed were recorded and compared to those obtained before and by others, helping to improve the following model. Which is what an engineer would do in order to improve a mechanical device. With regular observations and records Huygens collected a series of data, which supported the results, obtained without the need for a 'philosophical discourse'. Huygens claimed that his designs had improved the air-pump and said so in his correspondence. Huygens introduced a plate for the receiver, which neither Boyle nor Von Guericke had done and which facilitated the use of the pump. He was aware of how important it was to keep records of the observations and he compared them with those from other experimenters. Moreover, he showed, once more, his skills as an engineer because he designed several air-pumps looking for a good working device. This made Huygens once more unique amongst his contemporaries.

Huygens began experimenting with the air-pump in 1661. He replicated some and designed new models throughout 1662 (see figure 7). The most important designs and improvements were conveyed in his correspondence from 1661 to 1674[38]. In October 1661, Huygens said to his brother Constantijn that the machine did not work well[39]. There were some factors he thought would improve it, such as the length of the tube, which should be kept constant and made of thick leather. Huygens was aware, as a true experimenter, of the importance that certain factors had when recording the results of air-pump experiments to integrate them in scientific discourse. By November, the machine was working well because of these changes. Huygens claimed in several occasions that his was a better air-pump than Boyle's was[40]. Boyle also recognized that his machine was not as well adjusted as that of Huygens'[41] who invited Boyle to see for himself[42] the different changes introduced. It exhausted air better and it was kept in good working order for longer time[43], needing less adjustment every time it was used. Huygens always recognized Boyle and Von Guericke as the inventors[44].

Between 1664, 1665, and 1668 onwards, Huygens' experiments were less relevant than those from previous years. However, he worked on the column of mercury and communicated with Boyle through Moray[45]. Another aspect was taken into account: how the changes of temperature outside a tube filled with water or mercury would affect the liquid inside. He placed the tube in a bath of ice[46]. Huygens confirmed the results of these experiments and also for mercury with which a different level was reached[47].

The trials carried out had several objectives. The main objective was to prove that the vacuum existed. For this purpose, they aimed at creating an airless receiver, to defend the existence of the vacuum, as works by Boyle[48] and by Huygens showed[49], and to contradict Aristotelianism. They realized the potential of the new phenomena and how they could be applied to explain the physical properties of air. The trials were set up at different lengths of time, from some hours to the whole night to see how much air was pumped out. Experimenters tried to describe the properties of the elasticity of air. They carried out trials to prove it. On his part, Huygens admitted to his brother Lodewijk that the air expanded as Boyle's law showed[50]. Huygens used this law to calculate the density of the atmosphere at different altitudes[51]. They studied the compression of air with experiments under water. It was believed that the deeper the water, the more compressed the air was, and swimmers took part in these trials[52]. In order to determine this, Boyle suggested that the pump be taken to a depth of thirty-three feet; Moray advised a shorter distance[53]. In one of the experiments a swimmer carried a bottle and it broke at sixty braces. This was attributed to the force of the cold in deep water; cold had compressed the air[54].

Correspondence helped to diffuse the latest designs and experiments. When Huygens tried to build Boyle's air-pump following the instructions that accompanied the instrument[55], he thought that the stopcock should not be made of wood, as suggested, but of leather. He communicated this to Moray because he thought wood would make that part of the air-pump weak[56]. He kept Moray and Boyle up to date about his experiments. He began by duplicating those that appeared in Boyle's book: Physico-mechanical experiments on the air (April 1661), a copy of which Huygens had received by the summer. He believed that Boyle's work reflected the explanations to the effects of the void. The exchange of information was detailed and allowed them to replicate and check each other's experiments[57]. However, sometimes it was difficult to reproduce the trials from other experimenters' work. This was the case when Boyle wanted to duplicate Huygens' at the Royal Society in the summer of 1663.

The accuracy and precision of the air-pump experiments had to be calibrated, but against what? Torricelli's vacuum was used as a standard. If, as Torricelli had said, the height of the level of the column when performing the vacuum was 30 feet and it did not change as expected, it was thought that the air-pump leaked. It was, therefore, important for all the experimenters to be kept regularly informed about any results and any differences obtained, and about any new designs. Huygens commented that he was unable to understand some of the experiments in Boyle's book and asked for further explanation in his correspondence[58].

Huygens' most relevant experiment with the air-pump was the Torricellian vacuum. He observed the formation of two bubbles in the inverted tube. He asked Moray[59], Chapelain, or Sluse for advice on what caused the second bubble to rise. They said that the bubble was not caused by the mercury, but by the elasticity of the air in the closed tube[60]. Huygens continued experimenting using purged mercury and water. He found different results in both. He observed that when using purged water the columns remained at higher levels than in the known Torricellian column. But if some air was let in the vacuum, then the columns descended to the standard level as expected in the standard Torricellian vacuum[61]. Huygens confirmed the elasticity of the air and stated that the effluvia must emerge from the purged mercury, which filled the higher part of the tube, that is the vacuum, because the purged air inside had to be at equilibrium with the air outside the tube[62]. Other experiments on how air affected different elements in the vacuum were carried out. A flame within the void was extinguished within four minutes, but when air was let in, it lasted eighteen minutes[63]. They were aware of the time factor, which is so important nowadays, particularly, in protocols in the biological sciences.

In 1662, Huygens improved parts of the air-pump and built a new one. He questioned what physical properties water had because of the two bubbles formed in the column of water of the inverted flask used in the experiment of the vacuum within a vacuum. He believed that the first bubble was due to air, but a subtle matter caused the second one. This phenomenon baffled Huygens and he was unable to define it for years[64], as he wrote later to Gallois, in 1672[65]. These new phenomena appeared every time he replicated a test.

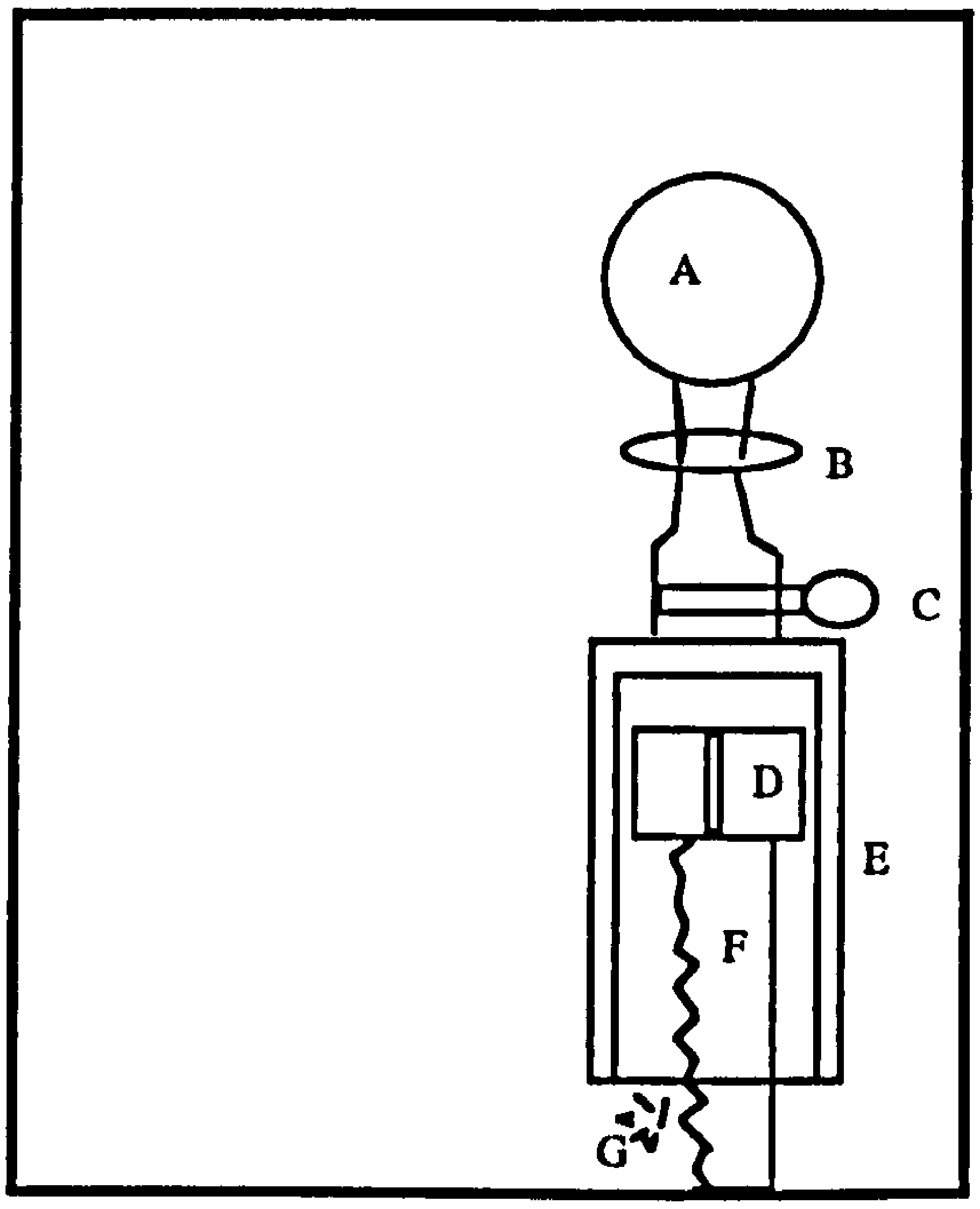
In 1662 and still in 1665[66], Huygens believed that the first bubble was created by air, but the second one was created by something else, maybe from air in the water. In 1668 he thought it was due to subtle matter. He applied the hypothesis of the subtle matter to explain these phenomena[67]. The same year Huygens had elucidated characteristics in water, which were not found in air[68] and concluded that the cause may be due to subtle matter. In water, particles were found one on top of the other, whereas in air, the particles flattened and moved as in a whirlpool. Therefore, the water suffered two pressures/weights: that of air and that of an even more subtle matter[69]. The issue was raised also in 1672, because he was still not satisfied with these conclusions[70]. The research carried out by natural philosophers during these years, with a new 'physical' instrument, brought about several changes to traditional thinking. Traditional philosophy was challenged by experimental science. Instruments were integrated within the new body of mechanics, and became essential to build the framework of data required to prove new hypotheses, which in turn, developed very quickly in underlying theories of the new experimental science. Therefore, experimentation required a new empirical framework with which natural 'researchers' were able to develop an empirical method and from it derive the necessary theories to explain new natural phenomena as they emerged, when factors and materials were changed in the experiments. For

Huygens, subtle matter brought about questions, which challenged his knowledge. Once it had made its appearance it had to be defined, discussed and proved, and for that new theoretical 'physics' had to be developed to explain how it worked in nature.

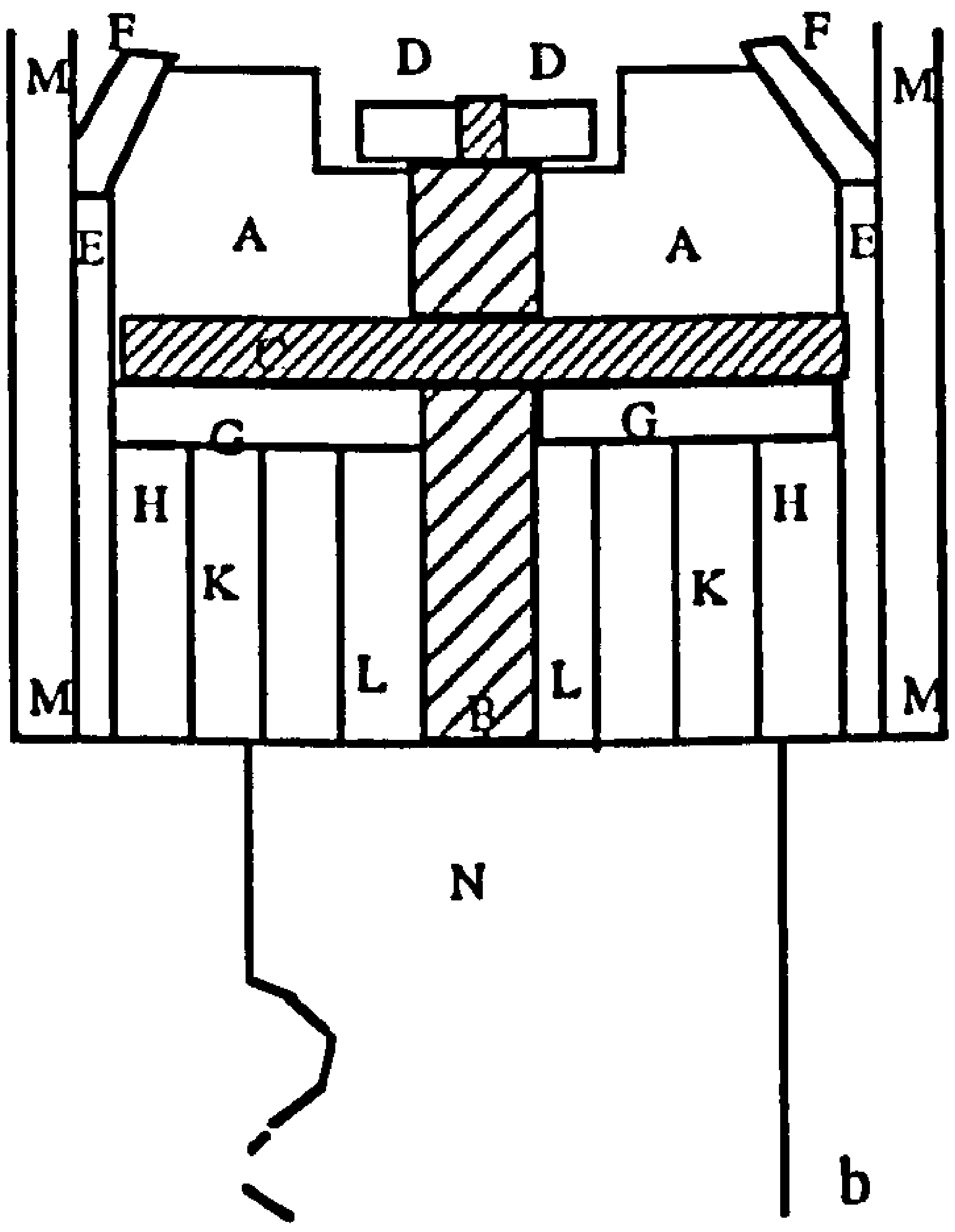
Huygens believed that subtle matter filled an empty space when there was no air. This matter exerted a pressure upon the empty space. He tried to prove that better experiments could be performed and reproduced more accurately if all the phenomena so far observed could be explained. He seemed to believe in the existence of a relative vacuum when he made the receiver airless, but not in absolute void, because he could not make the pump subtle matterless. He was unable to obtain absolute void because he could not think of what materials he could use to avoid the subtle matter traversing the receiver. The phenomena observed were explained when he deduced his theory of matter, in which the two bubbles had played a key role. Maybe this was the reason why he did not continue with the experiments, but passed the responsibility on to Papin in the early 1670s.

2.1. Huygens' air-pump, an improved model over Boyle-Hooke's.

From the first air-pump he made, Huygens had as an objective to make the receiver as airless as possible. To make it airtight, further improvements had to be made to the pump of Boyle and Hooke. In Huygens' model (figure 4a and 4b)[71], the receiver was on a platform under which he put the stopcock, wrapped in leather soaked in oil[72], with the rack and pinion to empty the receiver. These changes improved the air-pump in relation to Boyle's, which was weak in three important aspects: (i) the stopcock, which connected the receiver to the pump; (ii) the piston in the cylinder, which had to fit well; (iii) the seal of the receiver. Huygens realized this and made the appropriate changes to obtain a better working model.



a



b

Figure 4 (a -b) - (a) Huygens' first air-pump of 1661; (b) the piston of the 1661 air-pumps[73].

In figure 4a the receiver, A, was made of glass and turned upside down over the base-plate B, a metal dish filled with soft cement. The stopcock (*robinet*), C, was a wooden key wrapped in leather. D was the piston (figure 4b). E was the cylinder (2 inches, the outer-diameter; 2 1/2, the inner-diameter). F was the rack made of iron and G the pinion.

Figure 4b was the piston made up of rod B that formed a block with the rod of the piston traversing it. It was welded to the disc of iron CC on top of which a wooden disc, AA, was placed. The disc AA had a hole through which a small iron screw DD passed. Thick leather EE was riveted to AA and two small nails FF were fitted at each side at the top to keep E fixed. HHGGHH was a hollow section lined with pig's bladder. This hollow section was filled with pieces of cork: KK, LL, and to make the system more airtight, pieces of wool were introduced between them. GG was a chamois skin impregnated with oil and HH was a cylinder made of thick shoe leather. At the bottom of HHGG there was a hollow lined with thin pig's bladder soaked in oil to fit piston NN. The piston was then left all night in oil. Already in 1658 he had drawn machines to compress air (see figure 5) and he thought they could be applied to clocks or other instruments. It could be deduced from this that Huygens applied a similar principle to the first air-pump, but now he tried to empty a glass vessel (bell jar) of air rather than compress it. The compression of air was a subject already discussed by Mersenne in his Academy in the 1630s[74]. Huygens, however, did not mention it much in his works. Some drawings have been found of 1658 and some comments in the Journal of his trip to Paris and London of 1661.

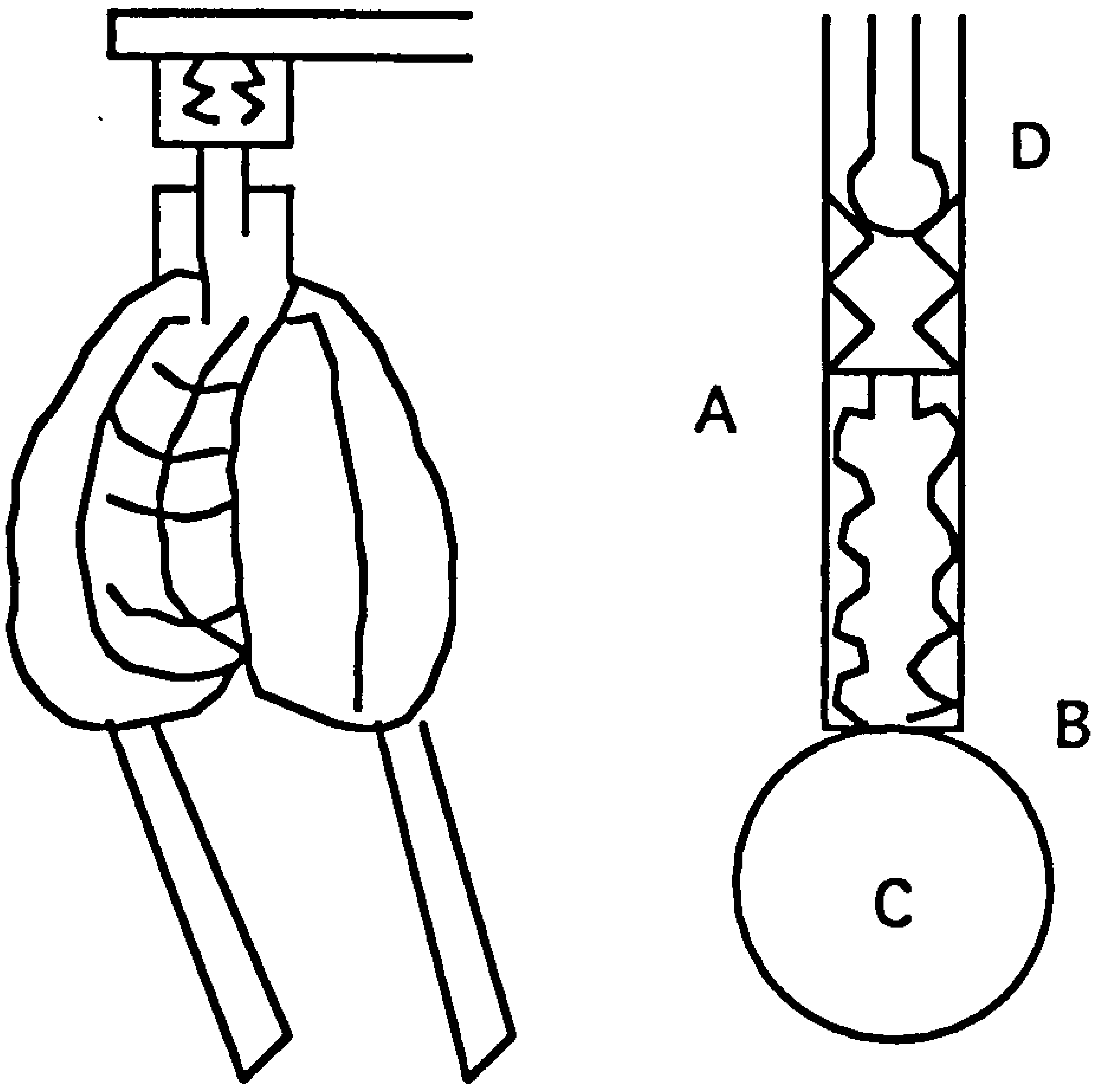


Figure 5 - The compression of air, drawings of 1658[75].

In the first experiment of November 1661, Huygens observed that his air-pump worked better than Boyle's did. He could keep a bladder swollen during a whole night in the airless receiver and he explained so to his brother Lodewijk the following day[76]. Huygens' air-pump was better designed and handier than Boyle's. It was easier for experimenters to use because of the leveled platform on which the receiver rested and it could be kept empty for longer time.

The four main features that made Huygens' pump more precise and air-tight than Boyle's were: (i) the position of the receiver, (A in figure 4a), which was placed upside down over a base-plate full of (ii) a viscose cement making it more air-tight than Boyle's[77]. This new cement (B in figure 4a) used to fix the receiver was better, as Huygens could prove, because the void lasted for long periods of time "whole nights" even[78]. It was made up of resin and yellow wax[79]. It adjusted the receiver against the base-plate better, making it airless longer.

Further (iii) the stopcock was wrapped up in leather soaked in oil[80], yielding a better fit. According to Huygens, Boyle's was simply made of wood, which could change size when temperature fluctuated. Another improvement not taken into account by some historians of science, such as Stroup, was (iv) the use of turpentine to make the stopcock turn more easily and so make it tighter if necessary[81].

Huygens showed his skills as an experimenter once more when he took into account how factors such as: size and shape, or the materials employed and those used to make the instrument, affected the results, which should remain constant throughout. He also realized that other features could be changed. It was important to put wool and cork in the piston to make the rack fit as well as possible. The piston was lined with leather soaked in oil so that the leather fitted better against the neck of the pump. All this proved that the receiver could be emptied more and better than before[82]. Since this provided a better fit of piston to cylinder, he was able to empty more air from the receiver[83] (figure 4b), and, as a consequence, improve the outcome of the experiments.

2.2. Experiments with the air-pump

The most important experiment was the 'void within the void'[84], as Pascal had already called it in 1647. This was the most influential of Huygens' tests on the void, and one that made him develop an explanation of the observed phenomena and to define the physical properties of air and water differently from that of his contemporaries. Huygens had performed experiments with Torricellian tubes, or with the barometer, as early as 1648. In the 1630s, Mersenne had been discussing in his Academy the Torricellian vacuum[85] and in 1648 wrote to Huygens' father, Constantijn, commenting amongst other things on the barometer, but without describing the experiments[86]. The same year, Mersenne also wrote to the young Christiaan on the experiments the latter had performed on the vacuum[87]. Huygens had attributed the swollen bladder in his experiment to some property of the air that rarified it. Mersenne wrote back saying that rarefaction was not understood and even Descartes had abandoned it[88]. In the same letter, Mersenne explained that in one experiment, when a finger of air was let into the void (the space above the column of mercury), it also caused the column to descend a finger. Whereas if water was introduced in this void space the column only descended 1/14 of a finger[89].

His aim was to develop an air-pump accurate enough to empty a receiver of as much air as possible. In 1659 Huygens received reports from Moray on the work Pascal had done on the barometer[90]. During the trip of 1661, Huygens maintained some discussions with Pascal about the void[91]. This year Moray commented to Huygens on the different experiments carried out at the Academy on the compression of air and water[92]. However, Huygens always seemed more interested in emptying the receiver of air, and in how to improve the instrument to achieve that.

In 1657 Huygens visited Antwerpt where he learned about Von Guericke's pumps through G.Schott's Mechanica-Pneumatica[93], as well as the Magdeburgium experiment which consisted of emptying a big glass vase of air. With this experiment Von Guericke's questioned the Aristotelian concept of *horror vacui*. From this it was not difficult to join both traditions together and to perform the void within the void experiment as Pascal called it. Boyle's pump of 1661 showed Huygens that the vacuum could be performed in small scale too.

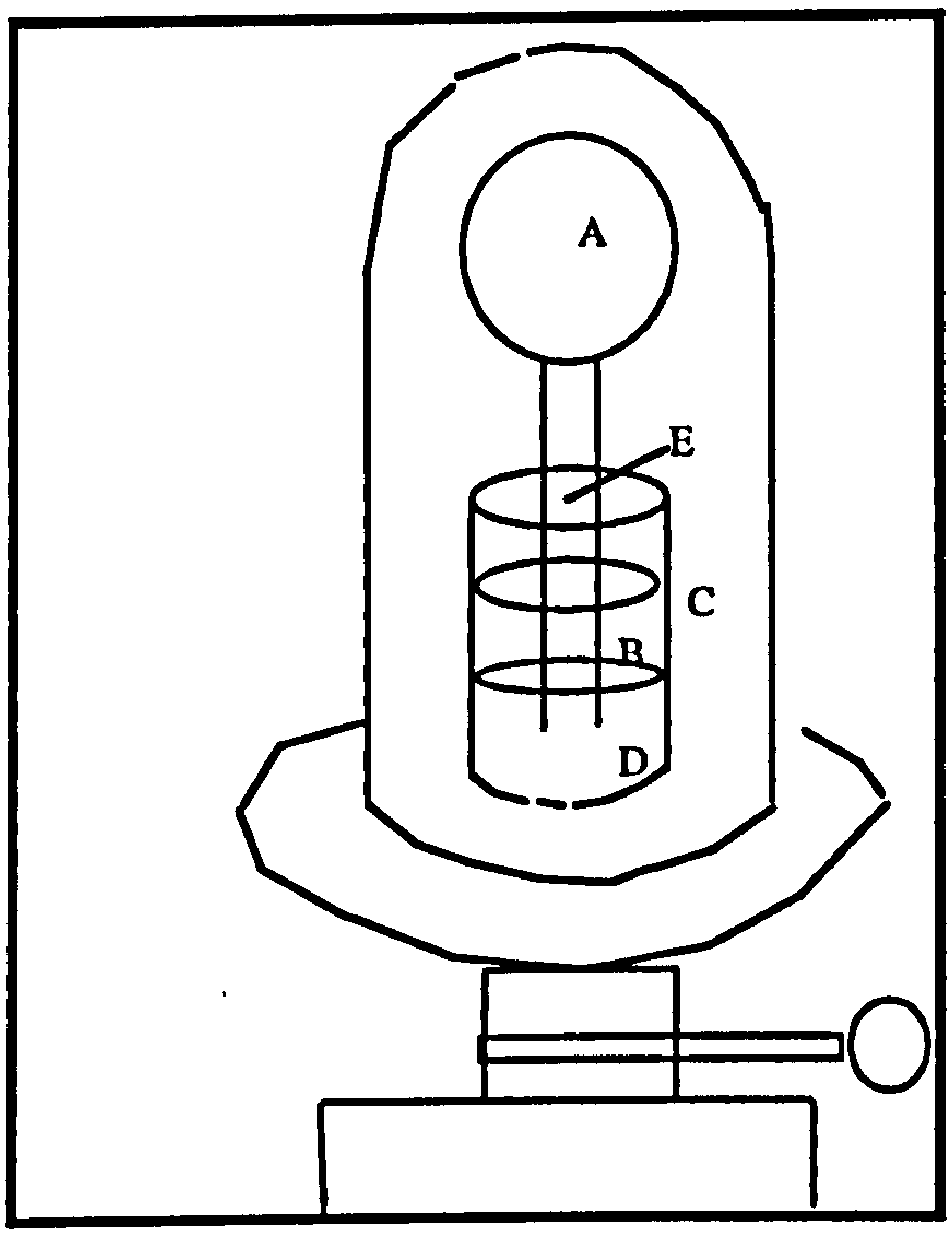


Figure 6 - Experiment of the void within the void (21 December 1661).

The experiment of the void within the void, consisted of an inverted flask A, filled with water and placed in recipient B which also contained water up to level D (figure 6). Then the air was pumped out and the water from A descended into B until it reached level C. When the air was let in again, flask A was filled with water but a small bubble remained at the base of the water in the tube of the flask[94]. The experiment of the void within the void: the Torricellian tubes were Boyle's number XIX. Huygens carried it out on December 1661[95]. In these trials, the water did not descend as much as expected; when the vacuum was performed a bubble appeared in it due to <u>anomalous suspension</u> (E in figure 6). (Anomalous suspension nowadays would be explained as residual air; surface tension; viscosity; weak attractive forces between fluid and glass)[96]. Boyle believed that it was due to the pump leaking, but Huygens had proved that his was a better pump because he could maintain the void for longer time and could exhaust more air from the receiver; and he had calibrated it with the standard experiments. Huygens thought at first that the bubble formed in the column of water was of no importance, but the water would have to be purged/drained of air to make it descend in the void. He thought that this bubble was due to air still left in the receiver and, therefore, more air had to be pumped out to allow the water to descend in the column. The bubble disappeared after some time, because it had entered the water again[97]. In this experiment, Huygens wanted to prove that air was heavy and elastic and could be emptied from a receiver creating a void. But soon he realized that there was another phenomenon so far unaccounted for, and which seemed to contradict the initial hypothesis that an absolute vacuum could exist.

The uncertainty over the second bubble formed in the column made Huygens use water drained of air in all the experiments of the void within the void. Some of these trials were performed at the end of December[98]. He thought that the cause had to be more than the weight of air and its elasticity. He did not mention how he drained the water of air, but it would not have been possible for him to drain it completely. By boiling the water he could not eliminate all the oxygen. Later on, he left the water in the inverted flask for twenty-four hours. He tried flasks two feet long, to see if a foot higher would make a difference, but without success, the two bubbles still appeared[99]. The results were the same for a 4-foot tube[100]. The water in the flask still did not descend and the two bubbles appeared in these experiments even when performed with water drained of air. The small bubble remained at the neck of the tube, whereas the bigger one sprung from the base of the former and expanded upwards, filling the neck of the flask[101]. This was a very important experiment; it was the standard used to check the accuracy of the air-pump. He was convinced that there was no air left in the water, or hardly any. Of the two bubbles, which appeared in the tube, the one remaining at the bottom was of air, but the one that grew as it rose in the flask must have sprung from the water. Huygens started to think that apart from air, water also contained subtle matter, which could traverse natural elements, solid or liquid, and, therefore, the receiver. This subtle matter was made up of particles smaller than air. However, he did not define what he saw in 1662[102] until 1672, as he explained in a letter to Gallois[103]. The subtle matter had the physical properties of traversing any natural element in the universe, solid or liquid.

To see if the bubbles of boiling water became bigger when the vacuum was performed, Huygens tried hot water (Boyle's Experiment XLIII); he also used small canaries (Boyle's Experiment XLI) and commented on the outcome in his correspondence. In a letter to Lodewijck, he compared his results with those found in Boyle's book. The small bird had died in the airless receiver and the hot water boiled with great bubbles as if it had been suspended over a big fire[104]. A feather was dropped from the top of the receiver; also, a pendulum was suspended from the top, inside the receiver. Huygens observed that, although the pendulum inside the receiver swung for longer time than if placed outside, the swings were increasingly shorter. Boyle had seen little difference between the swings of the pendulum inside the receiver, and the one he had put outside, on top of the receiver (Boyle's Experiment

XXVI). But, Huygens reported that the pendulum in the vacuum had stopped quicker than he had expected[105]. They compared their observations, suggested changes and studied which factors were affecting the results. Replication was essential in the new empirical science. Chapelain tried to explain Huygens' results in accordance with the theories of Democritus and Descartes'[106]. This argument did not satisfy Huygens[107], who was convinced that the problem would be solved only if longer tubes were used[108]. Chapelain insisted, convinced that Huygens had misunderstood him. Huygens tried to explain the phenomena of the two bubbles again; one of them grew quickly in the tube without taking all the space of the water, which simply descended around it, and increased its size at the same time[109]. Moray attributed the phenomenon of the bubble rising in the tube as the cause, or a consequence of the water descending in the tube while the particles of air were constrained by the water[110]. Boyle agreed with Huygens, he also believed that a long curved-bottom tube with the bottom part full of mercury would help to prove Torricelli's experiment better.

In 1662 Huygens communicated his results to his brother[111] and to Moray in London[112] asking if Boyle had performed any experiments and had noticed any difference using normal and purged water (see figure 6). He had carried out his experiments thirty times and had observed the same results in all of them, with some difference when using normal water and purged water[113]. The normal water descended to the level of the water in the vase, but the purged water remained suspended. Certain factors had to be changed to make the void work better and contradict Aristotle. Different liquids should be used besides water and mercury[114], as Huygens suggested several times through his correspondence with Boyle. Although he was expecting a prompt reply, the answer from Boyle reached him much later, because Rooke[115], the experimenter of the Royal Society who was to duplicate Huygens' experiments, had died[116]. This point is missed in some historical studies. It is important because it shows that from an Academic background had decided to work outside the university for the sake of the new emerging science and that not only "operators" and natural experimenters worked in natural philosophy. Some trials were carried out on human parts exposed to the void. Boyle's new experiment consisted of emptying a receiver, bigger than any made before. Into it Brouncker inserted his hands through two little holes. After seven attempts to perform the void he experienced pain that vanished when the air was let in. They even thought of making a receiver big enough to hold a man[117]. Huygens and Papin made these receivers in 1691[118].

Later in the year, when Huygens tried to reuse the pump, it did not work because the piston did not fit tightly in the cylinder[119]. He then made his second air-pump (figure 7) which was significantly different from the first one[120]. It was a normal thing for Huygens, the engineer, to continue improving an instrument and introduced more changes later in 1667 and 1668.

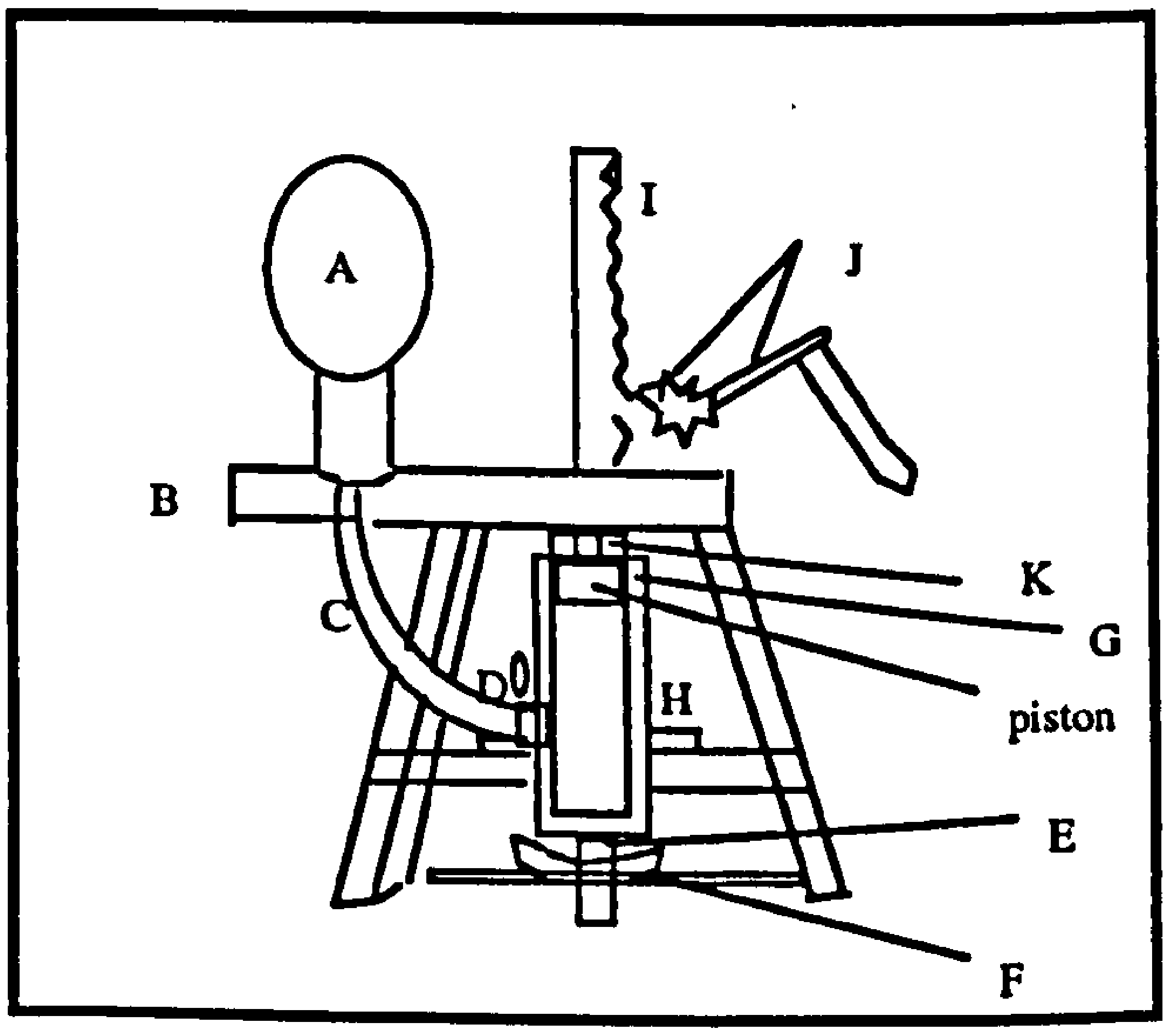


Figure 7 - Huygens' second air-pump of 1662.

The air-pump of 1662 (figure 7), consisted of a receiver A, a base-plate B, and a tube of brass or copper, C, which connected the base-plate to the cylinder. D was the stopcock; E was the leather valve; F was a basin to catch the dripping liquid; G was the highest point the piston could reach. H was the cylinder, about 14 inches long, with an external diameter of about 3 inches. I was the rack; J, the pinion and handle and K the space of about 2 inches above the piston, filled with a mixture of water and oil, which moved upwards and downwards with the piston[121].

This air-pump and later models were all more stable than the first, because they were built upon a wooden base. Another important change was the rack and piston (I/J in figure 7). The receiver and the base-plate were moved to the side (A and B figure 7). The stopcock was now located at the side of the cylinder (D in figure 7)[122]. The piston was drawn up in the cylinder to empty the air of the receiver, which was another important difference from the Boyle-Hooke's model; Huygens' pumped air out better[123]. In order to prevent the air from entering the cylinder and the piston from drying and shrinking, Huygens poured a mixture of oil on top of the piston[124]. Cement was another material that proved to be a very good change because it was kept soft for months. Boyle and other contemporaries took this up.

Boyle presented this model to the Royal Society in London[125]. In February, Huygens performed more experiments of the void within the void. The first one was of water drained of air. The water in the column only descended "*un pouce au-dessus du niveau de l'eau* *environnante*". However, when he tried with a small column of mercury drained of air, placed in a recipient also with mercury, the column of mercury only descended "*un demi-pouce*"[126]. Huygens said that there was more air in water than in mercury. The pressure of the air in the water increased the size of the bubble, which took up a lot of space in the tube of the inverted flask. He concluded that the air contained in the water expanded more than ordinary air. The proof was its size, similar to two grains of hemp seed. The water then descended slightly below its initial level. A double amount of air, under the same pressure, would have to expand twice as much[127]. On February, Huygens measured the weight of air[128]. He weighed the receiver with air: "*un livre 12 1/2 onces*"; airless it was less than "*9/32 demi-once*".

Meanwhile, he was introducing some important changes to the air-pump[129] that in 1663 became a new model. The Montmor Academy commissioned one[130]. The Academy had to wait until Huygens returned from his second trip to London, in the spring of 1663, because nobody seemed able to put it together[131]. The piston of the new pump could now be easily lowered and raised because it was placed on the side of the receiver. When Huygens returned, assisted by Petit[132] and Auzout[133], he spent a lot of time adjusting this pump[134] because it had not been used for a month.

During his second visit to London, the Torricellian experiment (figure 8) was duplicated without success[135]. They thought that maybe the water in London was different from that in Holland. Huygens placed a cylinder with some water (D) and a tube (C) turned upside down also filled with water. He first emptied the pump of air. The column behaved as expected in a Torricellian vacuum, the column of water in C descended and leveled with that in the small cylinder D. At that point, he believed that all the air of the receiver had been exhausted. Huygens then took this water and purged it of air and used it to reproduce the same experiment. When the receiver was exhausted of air, the water level in the tube still did not fall as had happened in previous tests. He thought this was due to the existence of the subtle matter in the liquid.

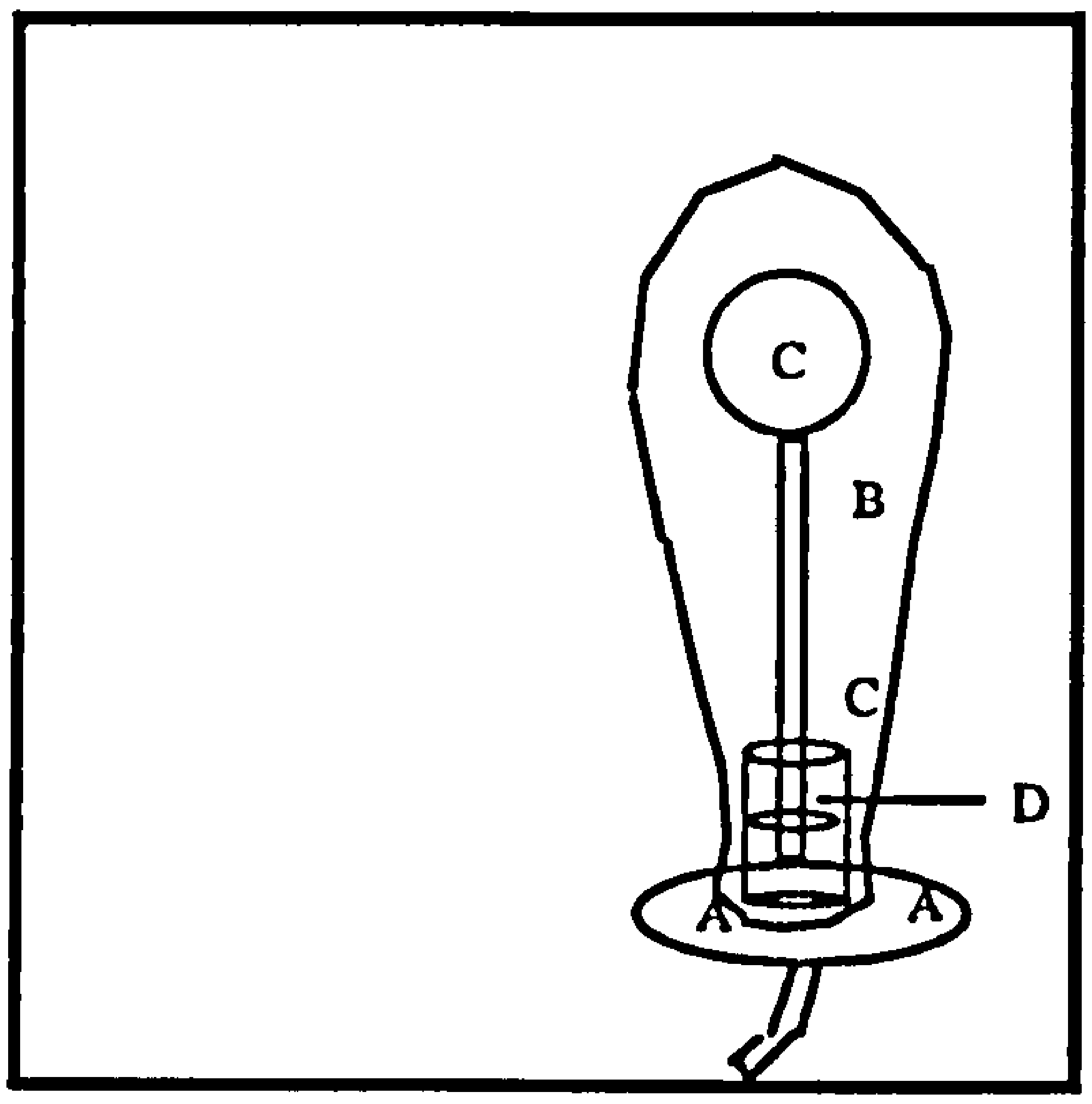


Figure 8 - Torricelli's experiment[136].

More sketches of pumps can be found in Huygens' notebook of 1667[137]. In 1668 he presented At the Academy another improved model of the air-pump with experiments[138] (on Saturdays from April to May). This improved model had a longer key in the stopcock, which made it easier to manage. The body of the piston had a cylinder of leather and fine thread wrapped around it[139].

In 1666 once at the Academy, Huygens made a list of possible experiments with the air-pump and submitted it to Colbert, who gave his approval by writing "*bon*" in the margin. In this instance, he agreed with all of them. It was a rule that any appointed member had to present the projects they wanted to work on to the Court bureaucrats. The five projects Huygens listed for experimentation were: (i) to perform experiments with the air-pump to determine the weight of the air; (ii) to examine the force of gunpowder and to conceal it in small amounts inside a ball of iron or leather strongly tightened (*espoisse*), which could be useful to the military; (iii) to analyze the force of steam[140]; (iv) to record the force and speed of air and its use in navigation and in machines; (v) to study the force of percussion and how motion was transmitted in the impact of bodies, for which he was credited with having given the first of the true rules[141]. This shows that Huygens was not appointed to the Academy only because of what he had achieved so far, but also because he could contribute with new experiments and the court could benefit from his new inventions. This proves that Huygens could design his inventions and carry out his own projects and research.

In 1672 some of the work with the air-pump was published in the Journal des Sçavans. It was mainly based on and referred to as the 1662 experiments. He experimented with sound by putting a clock inside the receiver with the alarm on, and none present at the meeting could hear it when the air was exhausted; it was only heard when the air was let in. The Accademia del Cimento reported the contrary in this experiment[142]. Huygens thought that this failure was due to the hole they had made at the top of the receiver to hold the clock from the outside. Huygens also tried organic matter; he placed an apple full of holes in a receiver exhausted of air, it swelled and liquid came out through the holes. Ethanol boiled in the void. Plants seemed to keep well for 24 hours, but when they were exposed to sunlight, they lost their strength quickly. He also tried to weigh an airless tube against a similar one full of air, or full of water. The experiment was not successful.

Heat seemed not to affect the void since butter did not melt when a hot iron was placed near the receiver, but did so quickly when the air was let in[143]. The Academy considered all these experiments, enough to prove the working of the air-pump and decided to move on to another subject. The standard experiments had been defined. Did this decision motivate Huygens to pass the air-pump on to Papin? The Academy did not question the results, seemed happy with them because they though that the vacuum could be proved, and because Huygens had built better air-pumps than contemporary experimenters had; proving also with the air-pump his role as a 'mechanical' engineer designing more accurate instruments.

2.3. Huygens' Barometer

Huygens was also to be involved in discussions with Hooke over the two liquid barometers. Huygens invented it (figure 9). He said so in his letter to Gallois[144], and to Jean Baptiste du Hamel and Oldenburg, and contemporaries recognized his claim[145]. He was the first to suggest the use of mercury and water in a barometer[146]. Nevertheless, with this barometer the surface of the less heavy liquid became dirty[147]. It was Hooke who suggested the barometer with three liquids, two of them being volatile fluids and was better than Huygens'. It did not get as dirty and provided better measures. The design was similar to that drawn by Huygens for Hubin to make[148]. Middleton does not seem to realize that the barometer of the three liquids was the same as Huygens' design of the barometer with two liquids and Hooke simply introduced a third liquid[149]. With Winter, I believe that Huygens was the inventor of the double liquid barometer[150] showing again his skills as an inventor with a new measuring instrument to his credit.

The observation and experiments with the void within the void had led to the work on the barometer. In May 1668 and in his address to the Royal Society Hooke mentioned the usefulness of the barometer. It could be used to predict the variation of the weather, for the pneumatic engine and for the spring of air. In the same paper, Hooke mentioned the work done by Huygens twenty years earlier with water in a tube enclosed in an exhausted receiver. Even when the pressure of the air had been removed, the purged water did not descend in the tube. This made experimenters in London try with 'quicksilver' mercury, instead. Hooke found that the mercury did not descend when the receiver was emptied of air, on the contrary, it stood twice as high as the usual height. Antagonists and non-believers in the vacuum used this to “overthrow the theory of the Gravity of Air”. However, the mercury descended as soon as the tube was moved to the height of the "mercurial standard" or "Torricellian Experiment", i.e. 30 inches. Hooke believed from then on that a subtle fluid existed[151]. He did not call it subtle matter as Huygens did, but fluid matter. Why did he not recognize it earlier? It was the Dutch experimenter who had called everybody's attention to this issue having found a new phenomenon in need of a new hypothesis. Although in these years Huygens was not carrying out experiments on the air-pump, contemporaries such as De La Hire made comments on the barometer with two liquids, and suggested ways in which it could be improved. Huygens recognized that with a longer tube to contain the water, the differences seen in the two liquids of the barometer would be accentuated (see figure 9, liquid B is below liquid A and it is shaded).

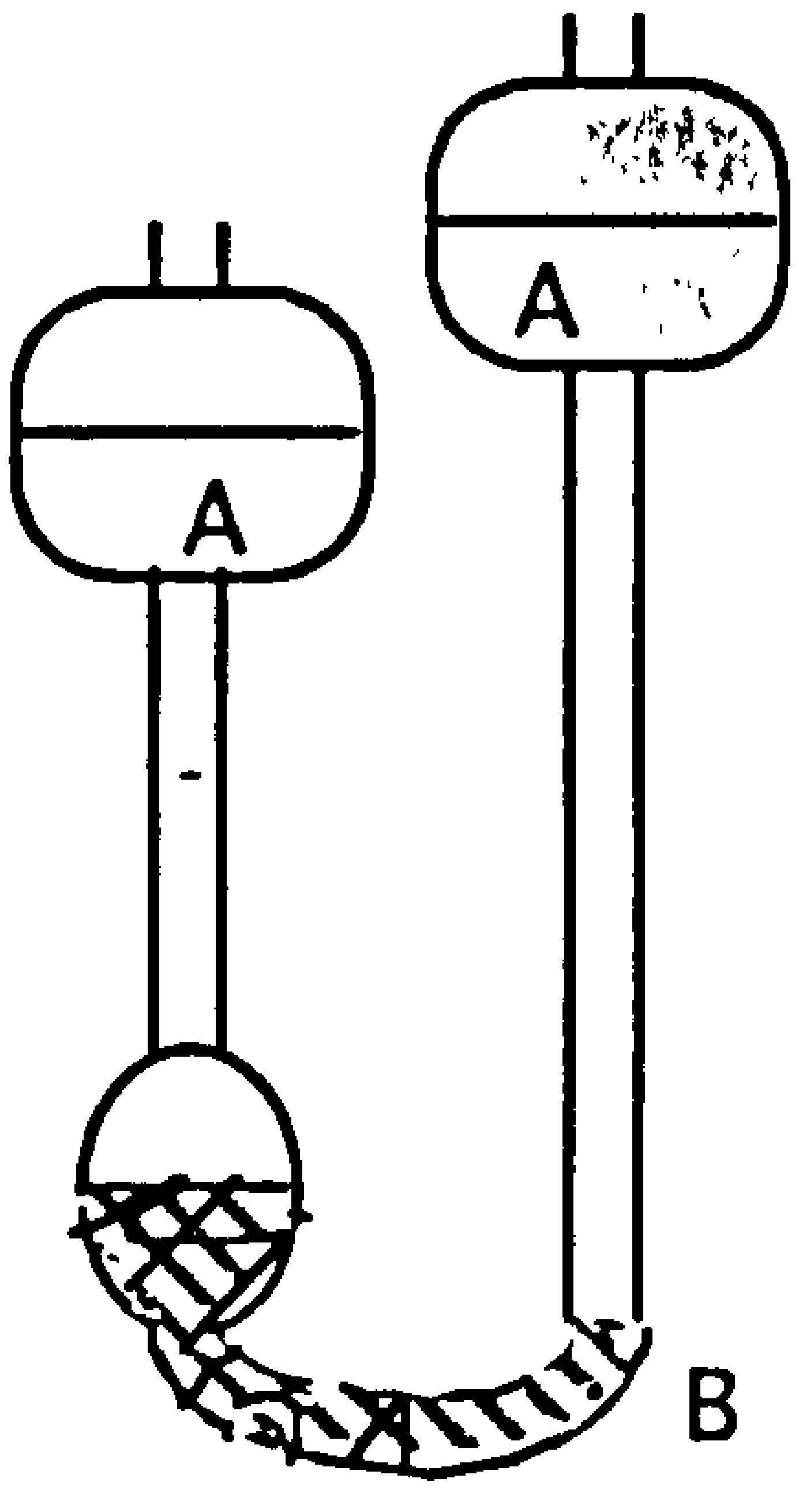


Figure 9 - Huygens' barometer of two liquids: A and B[152].

With the barometer and the air-pump, experimenters faced more challenges than they had originally imagined. Records were made as to what physical changes appeared when the receiver was made airless. They had to develop a new theory of physics to explain these records. It was more difficult with the air-pump because they had no device to measure the amount of air-pumped out.

3. THE BEGINNING OF NEW THEORIES IN PHYSICS

The air-pump was one of the first instruments to bring about more questions than answers in traditional science. These questions were discussed and new theories started to develop outside universities. Huygens was one of those experimenters who found in the air-pump a challenge to anything he had known so far. It was; therefore, important to have clear ideas as to how the instrument should work and what had to be achieved in order to make a standard and precise pump. It was also essential to evaluate and compare the results obtained and to standardize them. The final step in Huygens' work in this subject was to create a theory, to explain it all, the instrument and the phenomena observed.

Replication was essential to show how the air-pump worked and to demonstrate with the results of the experiments the hypothesis that a vacuum existed. That is why air-pumps had to be tested with the standard experiments as soon as a new design was introduced. Experiments were replicated In England and the Netherlands to standardize the use of the instrument. It was, therefore, important, not only to have an air-pump that did not leak, but also to be able to observe the outcome of the experiments and, most importantly, be able to evaluate them. It was better if other people were present to provide more objectivity about how much the original state of the object had changed inside the receiver while performing the vacuum.

However, leakage was a problem; it made replication difficult. A lot of time was spent trying to empty the receiver in order to make it more airtight. The replicability of experiments was difficult to achieve and Huygens realized that there was more to the air-pump than simply making it airless. It became necessary to standardize the use of the air-pump and to recognize the improvements that still had to be made upon it. This task was complicated by the multiple factors that had to be taken into account at the same time. The physical properties of air and other natural elements started to be defined.

Apart from exchanging new ideas and results, they also exchanged books. For instance, Huygens received Boyle's Tractatus de Restitutione Corporum in quo Experimenta Torricellliania & Boyliana Explicantur & Rarefactio Cartesiana Defunditur (London, Caemeterio Paulino, 1662 in 8°) in June 1662. By then Huygens was already trying to explain the anomalies of the void within the void, but he did not find anything new in Boyle's book of use to him.

From 1668, when he defined the cause of the bubble in the inverted tube, until 1672, Huygens' conclusions could be interpreted as those of a plenist. However, this concept was used to mean void of 'air'. When the air had been emptied from the pump, another matter: subtle matter, diluted infinitely (in the sense of many, many more times than water could be diluted), filled that space. The receiver could be made airless but not subtle matterless. Subtle matter could be found everywhere in the atmosphere. For more than ten years he searched for an explanation of this new matter and he introduced it in his work on statics of 1667-8.

Huygens wanted his air-pump to be impenetrable to both: air and subtle matter. The subtle matter, he was convinced, exercised an even greater pressure upon the pump than the air itself[153]. His system described the existence of four matters formed of particles in decreasing order of thinness. The first was ordinary matter, such as air, a very slow matter; the second matter was ether which transmitted light; the third was magnetic matter, with (*tourbillons*) electrical whirlpools within them; and, fourthly, subtle matter, which was the cause of the weight/gravity (*pesanteur*) of bodies and of the apparent elasticity of tangible bodies, solid and liquid. The particles of the subtle matter moved freely through solid or liquid bodies as easily as they moved through air[154]. Air particles could be trapped by both: subtle matter and ordinary matter[155]. Subtle matter could move at greater speed than any of the others, so that it kept the bodies down on the surface of the earth, balancing, therefore, the action of other matters with which the bodies would tend to move away from the center. Furthermore, Huygens believed in the existence of intermediary particles between air and subtle matter. In fact, he believed in an infinite progression of (*grosseurs*) sizes and different velocities of corpuscles. This infinite number of particles was very useful in the definition of the propagation of light.

By 1672, Huygens was fully convinced of the existence of a subtle matter able to penetrate anything, water, mercury, "even the glass of the receiver". It was exercising its pressure upon the column of water or of mercury, or upon solid objects such as he had observed with two metallic plates or marbles. The pressure exercised by subtle matter upon the water in the tube was independent from that of air. In 1686, Huygens developed it further in his Discours de la Cause de la Pesanteur and published it. In 1692 he still believed in a subtle matter which could move at greater speed than any other and which was the cause of the weight/gravity of all bodies. However, he did not come to terms with Newton's theory of gravity. He did not believe in bodies acting at a distance unless there was ether or other undefined matter holding them.

Huygens was aware of the need for further experiments on pressure studies[156]. It became imperative to define the physical properties of air, so that the different matters would be properly assessed. However, his experiments on the condensation and rarefaction of air confused Huygens even more when he tried to explain the observed phenomena.

He believed that the idea of the springs (*ressorts*) of air could satisfy most of the hypothesis, but he could not understand how it was possible to compress this fluid in a receiver, because so many springs were touching each other[157]. When a big weight was pressing on them, it made it difficult for other bodies that might want to pass. If for Boyle these bodies conserved the agitation (*l'agitation*) then the theory did not seem to hold together. Huygens said that Boyle used this hypothesis only as a project to explain the expansion of air[158]. On the other hand, Boyle had stated that the force of the spring of air was proportional to the space where it was compressed[159]. Together with Boyle's book: A Defense of the doctrine touching the Spring & Weight of the Air (1662)[160], Moray sent a table of the compression of air and dilatation[161]. Huygens wrote back showing a very easy formula to calculate the weight of air over a given height[162]. The weight of air above the column of mercury was found with logarithms, but Boyle preferred his own method based on the direct experiment[163]. Boyle continued with the experiments of "the spring of the air" and said that Huygens' reasoning about the two bubbles in the experiment of the void within the void was based upon the supposition that the receiver was void of air. Boyle recognized that he was unable to empty the receiver completely and thought that Huygens would be able to explain the phenomenon of the two bubbles, if he related it to air outside the receiver. Atmospheric pressure had to influence the void and the experiments made in it.

Boyle studied the weight of the atmosphere over a tube with mercury. If the tube was irregular and a finger bigger than the tube was applied, then "the atmospherical cylinder that presses against the finger will have a greater diameter than the Mercurial, and so will be able to sustain a greater weight". He added "the weight of the glass compared to that of water is 1 to 2 2/3 and its weight to that of mercury is of 1 to 5 1/4". The finger would expand inside the tube in the same way as small creatures did in the exhausted receiver[164]. In order to avoid leakage, Boyle was using the air-pump under water once it had been made airless. This, Huygens tried later. Boyle added that the "peculiar texture of some bodies"[165] might account for difficult phenomena. Huygens did not understand the relation that Hooke had made between rarefaction and the experiment of the tube filled with mercury. If a finger was placed at one end of the tube it would feel the pressure because of the weight of the atmosphere and the mercury from beneath. This led to an exchange of letters with Hooke and Boyle, where the phenomena of rarefaction was defined further and it was related to atmospheric pressure in the receiver. Hooke explained his theory of rarefaction[166] with a series of hypotheses for Huygens to understand the experiment of the tube with mercury[167]. The first one was the most difficult. It was assumed that there was an internal circular motion in fluid bodies. The particles of air were coiled in shape and became spherical because of the circular motion they followed. If a strong external pressure removed the coiled particles, then they were driven into less room, but without loosing their natural circular motion, or their power to keep a globular space. However, if they were compressed, these particles were more difficult to remove because their spherical space where they rotated had been decreased. A denser body, such as water, following the same hypothesis, was made up of bigger particles: globules. When Hooke sent this explanation to Boyle to clarify Huygens' problems, he called the latter "that Noble Virtuoso"[168]. What Hooke failed to see was that he had not created anything new and that he had not walked away from Aristotle completely, or from Cartesianism. However, he followed

Epicurus in his hypothesis of inherent/internal movement in particles and that was what Huygens found difficult to believe[169].

Why did Hooke wait twenty years to say what he thought about the anomalies observed by Huygens in his experiments? Perhaps, he did not understand them himself because he had not noticed them. The "pressing fluid" as Hooke called it was also able to traverse glass, water and other bodies impervious to air. He continued: "it was somewhat of the nature of the second element of Descartes". This fluid had the same pressure as air, but did not have to have the same spring[170]. Natural experimenters studied the properties of air but they did not distinguish clearly between pressure, spring, extension and weight of air.

During November 1663, Boyle also repeated Torricelli's first experiments. When the receiver was exhausted of air, the mercury was suspended higher[171] than expected[172]. When the air was let in, it descended. In Boyle's opinion, this test rejected Torricelli's hypothesis. Boyle observed that the different results might have been due to air pressure[173]. These were new phenomena for which no theoretical 'physics' existed yet. They were surprised by the results because they began with Torricelli's experiments as standard and ended up refuting him. Therefore, new hypotheses were needed.

Huygens continued his experiments with the air-pump until 1673 and 1674 when he let Papin take over. The bubble in the inverted tube, in an empty receiver, was now described as taking the space occupied by the water in the tube and the water was then exercising a pressure over it. The subtle matter was able to exercise a pressure on the tube and to traverse water and the glass of the receiver[174]. This physical phenomenon was taken from then on as a basis of what was observed in the vacuum and was used also by Papin in his experiments.

4. HUYGENS' WORK ON THE AIR-PUMP AFTER 1673; EXPERIMENTS IN COLLABORATION WITH PAPIN AND IMPROVED MODELS

Following the many trials with the air-pump, certain experiments had become standardized to test the precision with which the receiver could be made airless and, therefore, to calibrate the apparatus, or, as Huygens called it to see: "*sa bontè et justesse*"[175]. One of those experiments consisted of an inverted flask filled with water and placed in a recipient, also containing water, inside the receiver. The water of the flask could be fresh water, or water drained of air. When the receiver was made airless, the water in the flask should descend slowly to level with the water in the recipient. If the air was let in slowly, the water rose again in the flask, but if the air was let in suddenly, the water would raise so fast that it could break the flask.

In 1673 Huygens told Papin which experiments to perform[176]. In 1674 Papin's own improvements to Huygens' pump were known. One of Papin's pumps (figure 10a) had a cylinder instead of the spherical shape used by Huygens and was in line with the piston. He seemed to prefer Huygens' 1661 model, but with a double cylinder[177]. The second model of 1675 (figure 10b) had the cylinder to one side[178].

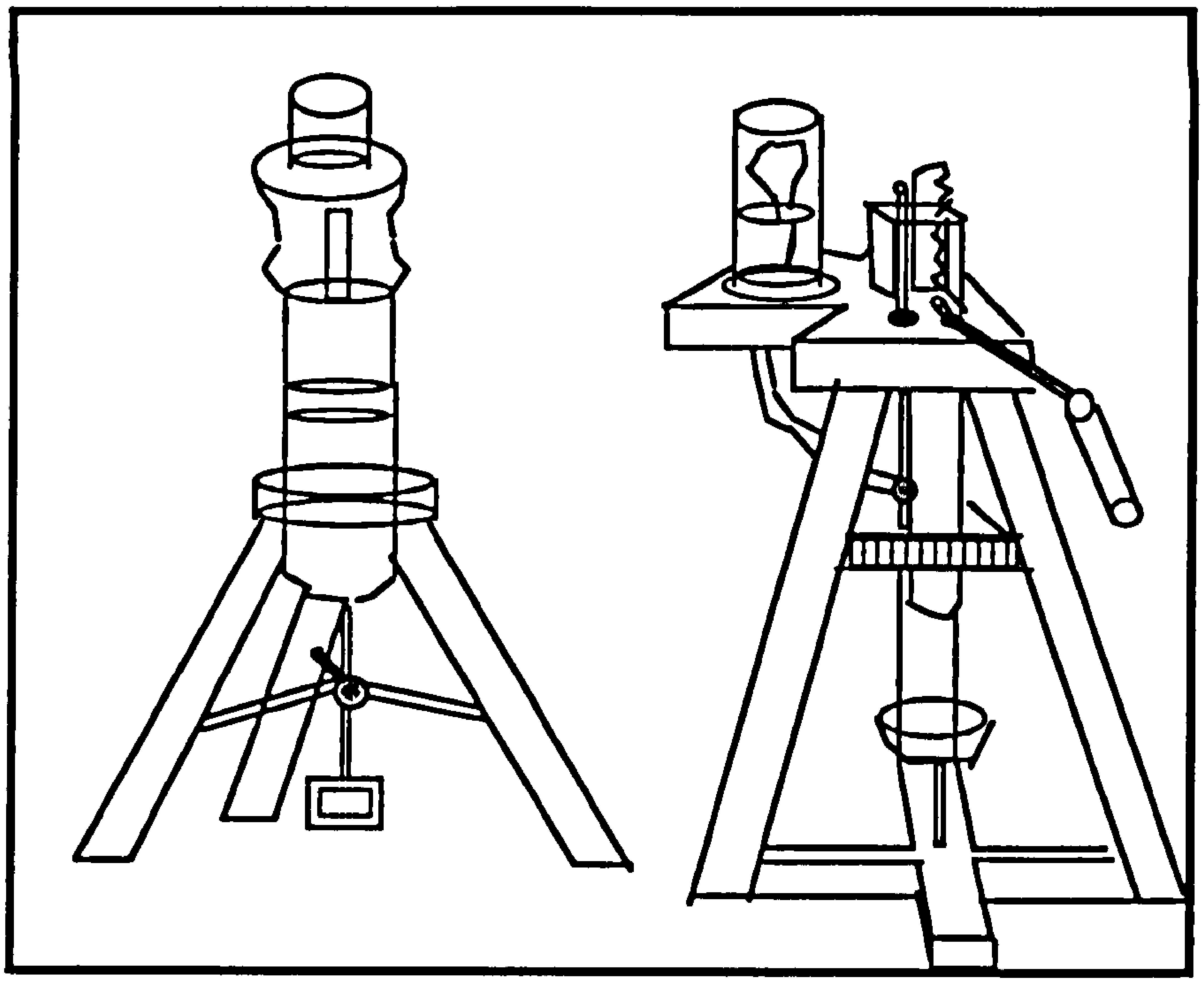


Figure 10 - Papin's air-pumps of 1674 (a) and 1675 (b).

Papin wanted to publish his work on the air-pump because he thought it worthwhile for others to know and benefit from it, so that they could set the apparatus up[179]. He asked permission for publication from Huygens, who had never published anything on the subject, except for the article about the suspension of the column of mercury in the Journal des Sçavans in July 1672[180].

The empirical demonstrations with the air-pump became more ambitious. Papin was able to measure the amount of air still remaining in the receiver. It was known that air sustained 32 feet of water and since the air remaining was ordinary air, it had to relate to the ordinary air as the height of the water in the flask related to the height of 32 feet[181].

Papin visited Boyle in 1673 and made a pump with two cylinders. Huygens had drawn the two cylinders that worked as a receiver already in 1662[182]. However, either Boyle, or Papin did not mention him, even though Boyle carried out some experiments in this pump in London. Maybe Papin had deduced the use of the two cylinders by himself or, he could have known about the possibility of using the two cylinders through Huygens, as he recognized in his dedication to Huygens when he published the work on the pump. Boyle referred to him as an 'assistant'[183]. It is right to say that Boyle created most of the "factual ground upon which late 17th century" English "experimenters operated"[184]. It can be added that, at the same time, Huygens and other French experimenters were doing likewise on the continent.

The objective of the new pump was to facilitate setting it up in a way that would yield the best responsible results. The experiments in general followed very much the standard ones made by Huygens, who suggested new ones, and Papin also developed some of his own[185]. They included plants, fermentations (ethanol (*esprit du vin*) and nitric acid) and also live animals. He observed that the lungs of animals, which had died in the airless receiver, sank to the bottom when placed in a recipient of water. Some of Papin's new experiments included the skin of animals (eels, sheep) and observed how the void affected them. He also tried eggs and gunpowder. The experiments with gunpowder were done with Huygens in 1673[186] and were successful since the gunpowder exploded in the void. This led to more sophisticated experiments which tried to make the receiver airless without the use of the piston. In 1679 Huygens continued experimenting with the air-pump, trying to find other possible uses. He said so to Pellison, who was writing the history of Louis XIV. He was experimenting with animals and objects which apart from some fruits, none had used before[187]. In 1679 Papin wrote to Huygens, asking him to obtain a pension for him from Colbert. In the same letter, he explained that he continued with his work in hydraulics and that Roemer had presented these on his behalf to the Royal Society, namely, a new pump with two cylinders, and some Digestor machines[188].

The experiments with small gunpowder charges exploding in the receiver showed the influence of Von Guericke's work, and Huygens had already worked with steam in 1666 as the projects he presented to Colbert show. Papin went further and tried boiling water that, in combination with the gunpowder discharges, shaped the way for the steam engine[189]. The cylinder was emptied of air, then a piston was pushed downwards by atmospheric pressure, this mechanical action lifted a weight at the end of a rope and pulleys[190]. Huygens carried out the experiment of the small gunpowder explosion in the receiver, but not as many times as Papin, who improved it, knowing that this was an easier way to perform the vacuum. As a consequence, he could reduce the atmospheric pressure of gases inside the receiver, and use it to perform mechanical work. When the piston was pushed downwards due to a lower pressure in the receiver, a large weight at the end of cords and pulleys could be lifted.

Papin was a Huguenot and had to live in exile after the Revocation of the Edict of Nantes in 1685. He took refuge in Germany, and was settled in Cassel by 1704. He was one of those professional Huguenots, whose ideas and experience were welcomed and used in the European countries where they found refuge. He always maintained correspondence with Huygens, exchanging ideas about their experiments. In Germany there were strong Galilean and Von Guerickean traditions in the development of instruments and machines for use in mines, such as water-pumps, and water wheels[191]. Papin was familiar with this tradition from his collaborative work with Huygens in France in the early 1670s. The aim of the experiment with gunpowder was to pull out most of the air of the cylinder using a non-return valve. This was quicker and easier than pumping air out. I believe with Talbot and Pacey that Huygens and Papin belonged to the Galilean tradition, in which machines were reduced to their basic essentials[192]. However, Huygens developed a new field in engineering accompanying these machines with a theoretical basis.

In 1686, Papin was working with the gunpowder discharge and its use in cannons. Huygens had written an anonymous letter on the ethics of the use of gunpowder for war. The letter was published in May 1678, in Les Nouvelles de la République des Lettres and it was titled: "Ad Majorem Dei Gloriam". It questioned why gunpowder was not put to better use than destruction. Papin agreed with this letter and seemed to know its source and since Papin was working with Huygens, it must have been written by Christiaan, who at that time could not disclose his identity because of his position at the Academy[193]. This could have also influenced the decision of the Academy who did not call Huygens back to Paris after 1683.

Although some historians believe that Huygens passed the air-pump on to Papin, in reality, the latter kept Huygens informed of all the changes he introduced. Papin reported the results of the experiments regularly. The experiments were similar to those carried out by Huygens between 1661 and 1662[194]. I believe that Papin's initial functions were those of a laboratory assistant who had been given full responsibilities over the pump and the experiments and who eventually became a researcher on the subject. Huygens appointed Papin mainly to confirm the replication of the experiments he had already performed himself. Since it was a question of duplication in order to standardize the air-pump, Huygens would not be as interested in carrying out these experiments himself, because Papin had acquired the expertise. In this way Huygens could dedicate his time entirely to other things, in particular, to the imminent publication of the Horologium Oscillatorium.

Huygens' association with his assistant Papin does not fit in a crude gentleman-servant relationship[195] as may have been the case in early Modern English philosophy[196]. They were collaborators performing experiments. Huygens also recognized the instrument makers' cooperation and, the instances when they had improved his instruments. Coster was given the right to claim the patent of the 1658 clock. It was a way of proving how grateful Huygens was for his help and collaboration. In the same way, Papin could make a name for himself by using Huygens' air-pump and experience and then by publishing his own results and making improvements. Huygens did not have to worry about status, or economic support, as he was already a well-known scholar at the time, nor had he invented the air-pump. He gave them a better chance because they showed they had acquired understanding and taken responsibility for their work.

4.1. Instrument makers and the air-pump. The development of the 'expertise in science' and the 'laboratory assistant'.

Gaudron, also a clockmaker was the instrument maker of air-pumps before 1673 for both Huygens and Papin. He was also a clockmaker until December 1678 when Hubin started to make them. Hudin was an Englishman[197]. He lived in France and worked closely with Mariotte[198], mainly making barometers, also for Huygens[199]. Hubin was *Emailleur* to the King[200]. However, Huygens did not pass on the right to apply for a patent on the air-pump to Gaudron because he always recognized Von Guericke as the inventor. Nevertheless, he did not mind Papin publishing a small book on the use and experiments of the air-pump. Papin was more than an instrument-maker; he was a technician and an experimenter. Huygens could not deny him publication of the tests and designs he had introduced himself.

In the 1690s, Huygens continued exchanging ideas with Papin who was then an exiled Huguenot holding the chair of Professor of mathematics at Marburg[201]. In their correspondence they described a variety of uses for the void. For instance, Papin said that fruits seemed to last longer and suggested the utility of the void for that purpose. Huygens and Papin seemed to have a common interest in finding all the ways in which the void could be put to good use rather than used for cannons and destruction.

Several important points need to be raised regarding Huygens and Hooke. Huygens developed geometrical and mathematical theories 'per se' to explain an instrument he had designed and tried and make the theory of an instrument a universal law for any future construction and use a similar instrument. This is what made Huygens so unique in the seventeenth century. Huygens was not a natural philosopher as Boyle and Hooke were if the definition of the latter is taken into account "the business of philosophy is to find out a perfect knowledge of the nature and properties of bodies and of the causes of natural productions, and this knowledge is not barely acquired itself" but to help man and advance his state[202]. This was well within the Baconian tradition, Huygens had already moved away from it. Huygens tried to find a theory to define the phenomena observed and explain the mechanics not only of air-pump but also of the particles involved in the results obtained by experimenting with this instrument. From setting up the instrument, to carrying out the experiments, to the analysis of the results made the air-pump a multifactorial instrument much more complicated than the clock with unknown characteristics for its operators.

Hooke, however, used some geometry simply to help explain his philosophical debates, as to support and clarify his argument. His geometry appeared in some lectures on light, on astronomy, on earthquakes. He accompanied his debates with figures to clarify or give a representation of what he was describing[203]. He did not create a whole theory on mechanics to explain any instrument. He was more interested on defining the observed natural phenomena and debate them in a manner "philosophical" whereas Huygens resorted to simple physical theories on particles and went further developing his own mechanical theory for the phenomena observed with the air-pump (see chapter 3).

It was in the mid-1660s that Huygens and Hooke were given full-time roles within their respective institutions; the former to work, as an inventor, connoisseur and 'specialist', in the Court of Louis and the latter, as a paid 'operator' in the Royal Society. Moray referred to him in his correspondence as "our operator"[204]. Nevertheless, Hooke managed to find the time to write and present his own work and in Huygens' correspondence he was called: natural experimenter. However, Huygens was given free rein to carry out his own projects at the Académie des Sciences. Hooke was the instrument-keeper of the Royal Society and had much less freedom to pursue his own interests. Huygens would have never been called that since he was given the place of an inventor with all the status of a well-known Scholar. The systems at the Academy and the Royal Society were different.

Huygens was an outstanding learned scholar, whereas Hooke earned recognition after years of work with Boyle in a similar manner as Papin did by working with Huygens who had the international fame, acclaim and authority in the world of science. Hooke's position was different from members not only of the Royal Society but also of the Academy. Some historians like to exploit the idea of servant-master, Hooke lived in Boyle's house with the servants; however, this did not make him a 'servant', it was a convenient arrangement. He was known as an "operator" at the Royal Society. He, like Rooke, carried out experiments, but he was not considered a servant.

In general, Hooke was paid for his work as an instrument-keeper; while Huygens received a pension as an eminent scholar invited by Louis XIV to join his wealthy court. Also Hooke was an operator keeping the instruments of the Royal Society in good working condition and reporting about results to other natural experimenters; on top of that he had to research on his own ideas and experiments. Huygens could dedicate all his time to his own work and he only had to report to Colbert or the court administrators. He had the same level of importance as everybody else in the Academy. Hooke was paid a salary as keeper of instruments, but Huygens was paid much better for his ideas. Does the pay make the gentleman? Furthermore, there was an important academic difference. Huygens was breaking away from philosophy with his great skills as a mechanist and mathematician, whereas Hooke's work was deeply embedded in natural philosophy[205].

In my view neither of those two differences made Hooke more of a servant than made Huygens more of a gentleman. The circumstances of their employment were different. Hooke was one of the first English salaried “technicians”. Instead of being an academic at a university, he was employed by a private organization. Huygens was a scholar and worked directly at the court. In addition, he enjoyed much more freedom of thought and action; he was engaged to work on his own ideas with others, in a team, but not for others.

Were there two new social groups emerging; that of the professional scientist and that of the technician? By a professional, I mean scientists who were given a place as expertise regardless of background and by technicians, I mean their assistants. Hooke would be a ‘technician’ by profession, but one who proved to be a scientist in some areas such as microscopic studies, just as Papin was for the air-pump. Nevertheless, Huygens would be an example of an independent engineer with a unique expertise capable of developing universal theories from his work on instruments, including the 'theoretical physics' for the air-pump (see chapter3 below) with a philosophical twist.

5. THE PHILOSOPHICAL TWIST

Huygens spent years trying to find the theory to define subtle matter. Unlike Stroup, who claims that Huygens stopped his work on the air-pump in the early 60s, I believe that he was instead deducing the theory, which would prove the air-pump as an empirical instrument. For this purpose, he had to find the philosophical twist to link together the philosophy of the time and the 'new physics' required explaining the phenomena observed.

Huygens' concepts of matter were not just a result of Cartesian influence, as many historians of science have put it. He was also influenced by the atomic theories of the time, those of Democritus and of Gassendi. Moreover, he developed these theories further creating his own. The studies in statics and dynamics and the work of 1669 on machines to measure the speed of air without philosophical explanations, show that Huygens was convinced of the existence of certain forces, or phenomena in nature, which required a physical explanation, not a philosophical one. However, he had to do with what he knew at that time. It was for Newton to deduce, from previous theories, the new general laws that seemed then to rule nature and the universe.

Huygens' worked with instruments of precision for which he was able to develop a geometrical theory. However, it was more difficult to deduce new theories from the 'physical' theories available at the time. In 1661

Huygens had no way of explaining the causes of the two bubbles originating in the experiment of the void within the void[206]. He shared his knowledge and his results with contemporaries, mainly by correspondence. Chapelain offered a simple Democratian explanation. The basic principle of this theory was the variety of elements made up of different atoms less mobile and with more cumbersome shape as the element became heavier (from fire to soil), it had to be the draining of air from the water used that did not let the water descend because the smallest and most curved atoms of air had been taken from the water, leaving a heavier element in the tube which could not descend in the column[207]. Chapelain's letter reflected the mood of the time for a more atomistic explanation of matter. Like Huygens, he knew about the Greeks' theories of matter. However, it was not until 1668 that Huygens applied them to explain physical phenomena in nature. By then he was convinced that subtle matter could be found in the whole universe, rather than in the water alone, as he had said in 1661 and 1662. With the concept of small atoms, the Cartesian theory of whirpools[208] and the atomistic theories of Gassendi and Democritus, he explained the physical properties and dynamics of natural elements. This was the origin of corpuscular philosophy in the seventeenth century. Later, this contributed to the development of 'new physics'.

With Stroup, I agree that correspondence and scientific meetings were an important way of solving problems and getting to know about new ideas[209]. It can be added that because of that, they did not find it necessary to publish everything. However, I disagree with her when she says that Huygens was more interested in the properties of air than in adjusting the apparatus. In my view, Huygens thought he had designed a good working air-pump and Boyle, held by Huygens as an expertise on the matter, had recognized this. Huygens then went on to explain the phenomena observed, which logically led him to the study of the properties of air and the theory of matter. One of the main factors was to avoid leakage of the air-pump. Huygens believed that the instrument itself needed further adjustments and he improved some of its parts, because as an engineer he wanted to create the best working instrument. He also knew how important certain materials were to replicate each experiment well. For instance, he made the stopcock of wood and used wax, which allowed a better sealing. He found that a different type of water would also affect the results. In this correspondence, scholars also recorded and discussed all the tests carried out and the changes observed in the materials or animals used in the void, advising and helping each other in the process. Huygens compared them with those obtained by other experimenters.

The question of priority of the invention was not in debate. The aim was to make a better operating instrument. This was sometimes difficult because they were unsure of what to expect when they changed the objects used, or parts of the instrument. They recorded the physical changes observed in materials, animals or plants during and after making the receiver airless as data. These changes were their results and the data they used as a reference when they replicated each test. They did not have a theory to explain them.

The most modern physics of the time, Cartesian physics, could not explain the phenomena produced in the void. However, Descartes had created a philosophy with a very different discourse from traditional philosophy. His line of questioning was used in the new science where natural phenomena were studied 'per se' and experimenters tried to explain them in mathematical terms. As a consequence natural experimenters asked directly to nature. The results were the answer but they could not explain them with the available theories and they had to develop others. The old Aristotelian philosophy was being substituted by new theories which could be changed as scientific instruments evolved, providing new data. Descartes' influence was felt on the Continent and in England alike, contrary to what some historians have stated. For instance, according to Henry (PhD, 1983)[210], there was little or no influence of Cartesianism upon English matter theories. Descartes was influential in the way theories of matter were defined in the Seventeenth century. For instance Hooke quoted Cartesian hypothesis several times in his work[211] and Boyle tried to explain with this philosophy some experiments of the air-pump[212]. Another source was the new ideas exposed by the Renaissance in the translations of the Ancients, in particular, Democritus, and his atomic theory. Gassendi's translations transmitted the Ancients' theories of atoms and developed them further. They seemed appropriate to explain the physical changes observed in the void, either for the objects placed in it (animals, fruit etc) or from the observer's point of view (e.g. the bell of an alarm clock was not heard by the audience when placed in the airless receiver).

It took Huygens more than 10 years to partially clarify the phenomena observed in his experiments. From achieving one aim: the exclusion of air from the receiver by the action of a piston, to the effect that the air might have upon the column of water or mercury within the receiver, and from then on to explaining the properties of what he called subtle matter. He tried to explain the existence of the subtle matter as a cause of weight/gravity (pesanteur: in the sense of exercising a weight pushing down from above, rather than in the sense of a weight being pulled by a force from below). He had an intuition in 1661, not an answer, and he thought about it for several years until he found a theory to explain the changes observed in the void.

Huygens' theory of matter deserves separate treatment (see chapter 3). With it he tried to define new laws of nature. A new way of questioning results and describing the phenomena observed was developing; a more physical way based on an atomic theory still without arithmetic, or calculus, but something else, which Huygens could not define as a general natural law. Newton was able to do that.

Seventeenth century natural experimenters understood the air-pump as a way to explain different phenomena in nature, not only mechanical but also physical. First of all, they were trying to create an instrument that would work well enough to prove Aristotle's concept of "*horror vacui*" in nature wrong. Secondly, they improved parts of the pump. Thirdly, they realized that a new experimental science was emerging, and they created standard experiments, which were reproducible. An instrument was sold with an accompanying brochure of how to construct it and the experiments which had been proved would reproduce well in anybody's hand, whether experimenter or amateur, making the pump accessible to the public. They started to develop 'theoretical physics' to explain the physical changes observed in living beings and objects.

The description of the air-pump was adequate in its day for the purposes for which it was designed. The problem was the good fitting and working of an instrument which normally benefits from a precise explanation before anybody can assemble it. In this sense, attendance at the meetings was important because the public was told how the instrument was set up and made fully operational. For instance, Huygens explained to the Montmor Academy in 1663 how the air-pump worked. In any time in history people have found it difficult to assemble a machine from a brochure or catalogue and everybody works it out better after a demonstration or an explanation. Why should there be any difference with seventeenth century natural philosophers, academicians of the end of the century, or amateurs who bought the scientific instruments for experimentation, demonstration in universities, or simply for fun?

6. CONCLUSION

Huygens' interest in the compression of air began in 1658. To this we must add the influence from Mersenne's meetings, where compression was one of the main issues discussed, and the fact that the vacuum existed as the Torricellian tubes of mercury showed. A more mechanical approach was introduced by Von Guericke based on water pumping in mines.

Huygens became instrumental in the dissemination and improvement of the air-pump in the Seventeenth Century through his correspondence with both English and French natural philosophers. Huygens and Boyle corresponded frequently with explicit explanations on each other's experiments and advice. These letters were a good way of clarifying their own thoughts and of getting further ideas for their experiments. It also proved to be an important connection between natural philosophers in Europe.

Huygens improved the design of the air-pump constantly. He collected more data with each experiment and recorded the new changes observed. He explained in his correspondence[213] that the experiments he had performed in 1662 proved that he had built a more airtight and efficient air-pump than Boyle's had. This allowed him to demonstrate the existence of another pressure, not accounted for before, that of 'subtle matter'. This matter traversed everything and exercised pressure on any objects, solid or liquid, placed inside the receiver. Later, in 1678, he tried to explain weight/gravity and continued until 1686, when he developed a better definition for it.

The functioning of the air-pump was better understood if the experiments were observed. It was a new instrument with still undefined properties and it was difficult to operate when only following a series of instructions from a catalogue. It was important not only to see how others worked with it, but also to be present at the meetings in order to understand the phenomena observed with experiments on living things or even sound and how to carry them out. His interest in a theory to explain how sound was transmitted by particles could have derived from these experiments. He also worked exploding gunpowder charges, which emptied the receiver of air, thereby, moving the piston downwards, a mechanical action that could be used to lift a weight. Papin continued with this in the 1690s and after Huygens' death, up to the beginning of the eighteenth century.

Huygens had very clear aims when he built the air-pump. Making the receiver airless could prove the existence of the vacuum. And he knew that he required a good, precise instrument to perform experiments in order to show the existence of that void. Therefore, three points had to be studied. The first one was the philosophical aspect, to prove Aristotle wrong, the second, an explanation of the observed phenomena was needed new physical theories. Lastly, there was a mechanical approach, the building of more accurate and easier-to-handle instruments. With the experiments it was possible to do both: to see how new designs improved compared to previous ones and to carry out demonstrations for everybody to see, including people who had no training on the instrument. At first, the aim was mechanical; the objective was to find a good working instrument. Then it became empirical and certain standard experiments had to be created for anybody to be able to use the air-pump and calibrate it. Performing experiments in the air-pump opened the door to an unknown physical world, which prompted the development of the 'new physics'. The new phenomena discovered were no longer independent, they related to many others. The equation was one of many factors needing definition and new theories to explain them. This developed into an empirical science using experimentation to prove new hypotheses and was taken up by the universities in the 1670s after Rohault's works in physical science were published. Experiments were standardized to show the different physical properties of air. New instruments were created too, such as the barometer used to find the pressure of air.

Huygens' correspondence between the end of 1661 and 1663 showed that these were years of experimenting with the air-pump. He worked hard at improving the performance of this instrument, with new designs for some of its parts. The aim was to make the instrument more precise and the receiver as airless as possible. With this theory Huygens believed that the receiver had been made airless. Further experimentation in the airless receiver led to the study of the action of the pressure of air upon columns of water and mercury. The designs of 1672 were similar to those from 1663. The receiver was moved to one side; this allowed for the piston to move more freely, giving the user more room to manoeuvre, and to empty the receiver more effectively. It simplified the use of the air-pump. Boyle and Hooke were convinced that Huygens' air-pump was better; the results were more spectacular. One of Huygens' aims was to make the air-pump easy to use because although it is obvious that air-pumps became easier to handle because they were used more –rather than because they became popular (Helden, 1991 and 1994)- his devices helped in this process because of the materials used. Working as an engineer, he perfected parts of the device having learnt what had to be changed to achieve this after carrying out certain standardized experiments.

Vacuum of air existed, but not total vacuum, because of the subtle matter left in the receiver after emptying it of air. He had no mechanical means of making a receiver subtle matterless. Huygens found it difficult to believe in total vacuum if the subtle matter was taken into account. He did not know how to empty this matter from the receiver. According to Mariotte, the top of the tube was filled with a certain aerial matter (*matière aërienne*) exhaled by the mercury as it descended, but he did not believe in subtle matter[214]. It was also difficult for contemporaries to comprehend the phenomena that experimenters of the air-pump tried to put to them. An example was seen above with Chapelain. Huygens needed several letters to make him understand what he had observed, never mind what the cause of it was.

Huygens appears once more to be an exception to the natural philosophers of the time. He did not require metaphysical or philosophical explanations as such for his experiments. He deduced his own "physics" to explain them. At the same time he drew designs of every part that needed improvement. Most importantly, he searched for solutions to questions, which had not been answered before, or which had remained unconvincingly added to other conclusions and concepts. Therefore, two lines of thought can be seen in his works, including the air-pump. He was the instrument-designer, the engineer, who tried to build the best working model and, he was also the theorist trying to explain how the device functioned. In the case of the air-pump, any phenomena observed while carrying out experiments were recorded and a new theory of matter developed from these data. Huygens' belief in a subtle matter should not be confused with the Aristotelian concept of the plenum. This matter could traverse glass, water or any other element. By 1668 he had a theory to explain previous observations. As an engineer, he tried to find other applications for the new instrument. He thought that he could apply the principle of the cylinder emptied of air to the clock and for other purposes such as the crafts. He could make the air-pump airless but not subtle matterless. This contradicts van Helden's view that Huygens became a plenist later (1991). On the contrary, Huygens created another way of experimenting and of seeing the air-pump. Maybe another pump had to be created to be able to obtain absolute vacuum. Huygens left it there and simply developed his theory of matter to explain the phenomena so far observed with the air-pump he had designed.

Huygens shows a doing away with tradition, from Descartes' whirlpools to an atomic theory based in atoms moving in all directions. He broke with an older philosophy of nature, and tried to open the doors of a new one. He moved from a complicated world of physics based on philosophical dialogue to one where scientists could decipher natural phenomena in simple universal laws with arithmetical notation and scientific discourse. Huygens can be seen as a link between the old tradition, including Cartesianism, from which he had already distanced himself, and the emerging of the new science. It can be concluded that Huygens was breaking away from traditional philosophy and reaching novel fields of science by the use of original instruments whose results demanded new theoretical 'physics' to explain them.

Huygens joined both the old philosophical tradition and the mechanics and physics required to explain the new instruments and new phenomena. He designed air-pumps with the aim of improving their accuracy and developed a theory to explain how they worked and the results obtained. Huygens went further than merely offering an empirical outlook and developed his own theory of matter that defined the physical properties of air and the existence of different matters in nature by regularly developing his studies on motion dynamics.

Vol.2, p.207, carabine à vent, Vol.17, p.306-7).

[2] (Shapin, S. and Schaffer, S. Leviathan and the Air-pump, Princeton University Press, 1985).

[3] (15 Sept.1672, Vol.7, p.223).

[4] (Dec.1972, Vol.7, pp.238-241).

[5] (Gasparo Berti (1600-1642) tried to imitate some of Porta's work but rather than using the limit standard 30-feet high tube, he decided to try with a vertical lead tube 36-feet long. This tube, filled with water had a valve at the bottom of it and it was immersed in a vessel, when the valve was opened, the water would settle at the 30-feet level. Pacey, 1980, pp.117-122).

[6] (Pacey A., the maze of ingenuity, MIT Press, 1980, p.132).

[7] (Pacey A., 1980, p.121).

[8] (Guericke, Otto Von. The new (so-called) Magdeburg experiments of Otto Von Guericke, 1672. Translated by M. Glover Foley Ames. Kluwer Academic Publishers, 1994, pp.155-160).

[9] (Pacey, A., 1980, pp.117-122).

[10] (Stroup, 1981, p.142).

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[11] (Stroup, 1981, p.143).

[12] (1662, Vol.7, n.1163).

[13] (Middleton, 1964, p.37; Mersenne, P. Novae Observations physico-mathematicae, Paris, 1647, p.216).

[14] (Middleton, 1965, p.6).

[15] (Middleton, W.E.K. The Place of Torricelli in the History of the Barometer, ISIS, Vol.54, 1963, pp.20-2).

[16] (Middleton, 1963, p.25).

[17] (R. Westfall, Construction of Modern Science, C.U.P. 1989, p.46, 48).

[18] (R.S. Westfall, 1989, pp.44-7).

[19] (Helden, Anne C., The age of the air-pump, Tractrix 3, 1991, pp.149-172).

[20] (Middleton, 1964, p.72).

[21] (R.Hooke's Of Aerostatick Instruments, Middleton, 1964, p.145).

[22] (Middleton, 1964, p.49).

[23] (R.S. Westfall, The construction of modern science, 1989, p.114, 117).

[24] (Vol.1, p.84).

[25] (Vol.2, p.469).

[26] (Vol.1, p.75, 84).

[27] (Vol.1, p.91).

[28] (Vol.3, p.109).

[29] (Vol.3, p.248).

[30] (to Lodewijk, Vol.3, p.276, 384).

[31] (Vol.3, p.283).

[32] (Vol.3, p.265, 276).

[33] (Vol. 4, p.514)

[34] (Vol. 3, p.280, 285).

[35] (Vol.3, p.369)

[36] ("Je seray savoir Monsieur Boyle ce que vous dites de son present. Je suis ravy que vous ayiez fait une machine comme la sienne. Nous nous sommes proposé de reformer un peu celle qu'il a donné à la Societé principalement en ce qui touche l'exclusion de l'Air du Cylindre. mais puisque vous estes aprés la construction d'une a vostre mode, je crois que nous difererons la reformation de la nostre jusqu'a ce que vous aurez fait la vostre. C'est pour quoy vous nous devez faire savoir tout ce qui touche la façon de celle que vous allez faire", Vol.3, p.369).

[37] (Vol. 17, p.313).

[38] (Shapin & Schaffer, 1985, p.235+).

[39] (Vol.3, p.384, 389).

[40] (Vol.4, p.240).

[41] (Vol.4, p.85).

[42] (" Monsieur Boyle poura aussi juger de sa bontè e justesse", Vol.3, p.439).

[43] (Vol.4, p.275, 297).

[44] (Vol.4, p.150).

[45] (Vol.5, p.116, p.130, about a new thermometer by R.F.Sluse p.138).

[46] (Vol. 5, p.345).

[47] (Vol.5, p.360).

[48] (R. Boyle, Defence of the Doctrine touching the Spring & Weight of the Air, 1662).

[49] (Ch.Huygens: Works in Statics Vol. 19, 1668, unpublished).

[50] (Vol.4, p.85).

[51] (Vol.14 1662, pp. 483-490; 1668, 491-4; Vol.4, p.171).

[52] (Vol. 5, p.81).

[53] (Vol.5, p.84, 93, 100).

[54] (Vol.5, p.427).

[55] (Vol.3, p.359, 371).

[56] (Vol.3, p.384).

[57] (Vol.4, p.297).

[58] (Vol.3, p.320).

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[59] (Vol.5, p.41, and to G.A.Kinner A Löwenthurn, p.196, kinner's answer about the experiments he saw in Italy on the Torricellian vacum in 1655, p.217).

[60] (Vol.5, pp.121-2, "experientia compertum est quod sequj indicaveram, nempe Mercurium absque bullis non casurunm, et unam sufficere quae ipsius casum ad folitam altitudinem determinaret" and "ut numper in experimento Torricelliano, cum pondus aeris in vase clauso deesse videretur, vis elastica ingeniose substituta est").

[61] (Vol.5, p.221).

[62] (Vol.5, p.253, "Quod si Mercurius ab aëre (ut Nobilissimus Hugenius loquitur) hoc est, à Mercurialibus effluviis repurgetur; aether in superiori tube parte stabulans repletur pancioribus effluviis, ideoque minorem habet vim dilatativam, minùsque Mercurium ab aëre externo suspensum deprimit. Hinc fit, ut Mercurius non ad quamcunque, ut arbitror, sed solùm ad majorem altitudinem ascendat, tandemque ad certam mensurum pertingat, donec inter aërem externum and Mercurium internum fiat aequilibrium", the response from Kinner commented once more on this phenomena of purged and non-purged mercury and how they behaved differently, pp.272-4).

[63] (Vol. 5, p.238).

[64] (Vol.3, p.439).

[65] (Vol.7, pp.201-6).

[66] (Vol.4, pp.437-440; Vol.5, p.221).

[67] (Vol.16, p.186).

[68] (Vol. 16, pp.185-6).

[69] ("l'eau soustient ... non seulement du poids de l'air mais de cette autre matiere plus subtile dont ont a connu la pression par mon experience du vuide". Vol.7, p.201-6, 1672; Vol.4, p.439 (6-9) and p.440 (1-3)).

[70] (Vol.7, pp.201-6).

[71] (Vol.17, p.313 and 319 respectively).

[72] (Vol.3, p.384).

[73] (Vol.17, p.313, 319).

[74] (Mersenne P. Correspondence de P.Mersenne. Commercée par Mme P.Tannery, publié par Cornelis de Waard, Paris, Vol.II, Presses Universitaires de France, 1936).

[75] (Manuscript A, in Vol.17, p.305).

[76] "ma pompe pneumatique a commencè d'aller depuis hier, et toute cette nuit une vessie y est demeurée enflée, sans que pourtant il y enst auparavant presque aucun air dedans ce que jamais M.Boyle n'a pu effectuer" (Vol.3, p.395).

[77] (Vol. 17, p.313).

[78] (Vol.3, p.439).

[79] (Vol. 17, p.313).

[80] (Vol.3, p.384; Vol.17, p.313).

[81] (Vol.17, p.313).

[82] (Vol. 3, p.439).

[83] (Stroup A, 1981).

[84] (Vol.17, p.322).

[85] (Taylor, E.G.R., The Mathematical Practitioners of Tudor & Stuart England, CUP,1970).

[86] (Vol.1, p.75, 77, 84, 88; Vol.2, pp. 564-5).

[87] (Christiaan's letter to Mersenne has not been found).

[88] (Vol.1, p.88).

[89] (Vol.1, p.90).

[90] (Vol.2, p.469, 496-7).

[91] (Vol. 1, p. 84; Vol.3, p.46. Pascal's Nouvelles experiences touchant le vuide faites dans des tuyaux avec divers liqueurs, Paris, Margot, 1647, in 8°).

[92] (Vol.3, p.305, p.317).

[93] (Vol.17, p.258. Vol.2, p.389, most of the title of Schott's Book: Mechanica Hydraulico-Pneumatica qua praeterquam quod Aquei Elementi Natura, proprietas, vis motrix, atque occultus cum aére conflictus à primus fundamentis demonstratur... Pars I: Mechanicae Hydraulico-pneumaticae Theoriam continet. Pars II: ... Machinas que

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Aquarias innumeras, uti & organa, aliaque Instrumenta.... Accessit Experimentum novum Magdeburgicum, quo vacuum alii stabilire, alii evertere covantur. Sumptu Heredum Joannis Godefridi Schönwettery, Bibliopoli Francofortensis. Excudebat Henricus Pigrin Typographus Herbipoli. Anno MDCLVII. in -4°).

[94] (At this point, Huygens was not sure of what was causing the bubble. Boyle, in Experiment XXII, had suggested that the water contained some air or that part of the water was thinner than the rest. Vol.17, p.316).

[95] (Vol.17, pp.316-7).

[96] (Shapin and Schaffer, 1985).

[97] (Vol.3, pp.424-5; Vol.17 p.322).

[98] (Vol.17, p.320).

[99] (Vol.4, pp.23-4)

[100] (Vol.4, p.51).

[101] (Vol. 4, p.53, 97, 111, 201).

[102] (Vol. 4, pp.23-4).

[103] (Vol.7, pp.201-6).

[104] (Vol.3, p.397).

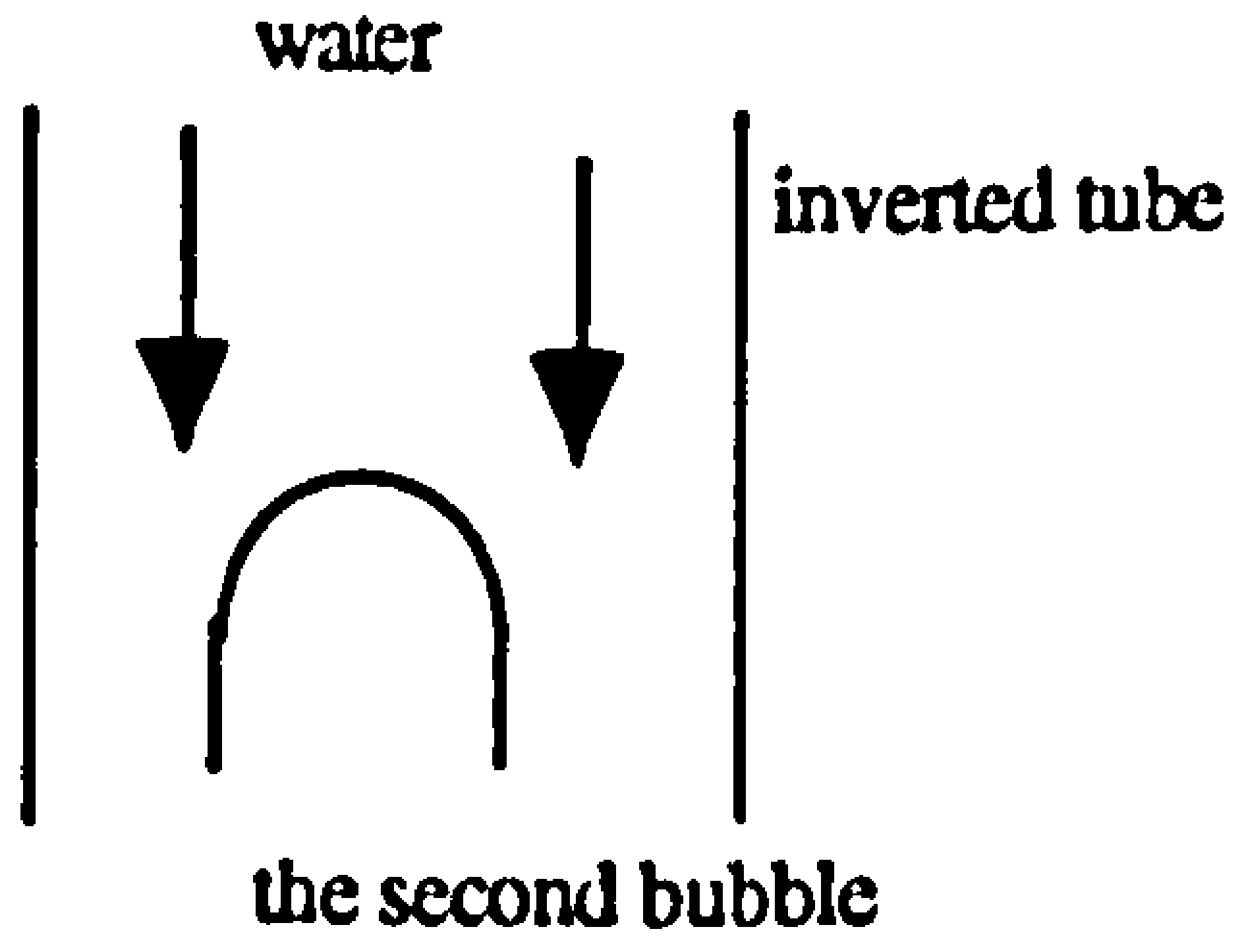
[105] (Vol.17, p.314).

[106] (Vol. 4, p.113, 119).

[107] (Vol. 4, p.53, 150).

[108] (Vol.4, p.98).

[109] ("c'est l'eau qui descend le long de ces parois, laissant le chemin du milieu libre a l'air" of the bubble". Vol. 4, p.146:



[110] ("la descente de l'eau lors qu'une petite bulle monte au sommet du tuyau, puis que les particules d'air qui ont cosntraints à se referrer dans peu de place tant qu'ils se trouvent comprimez de tous costez par l'eau, aussi tost qu'ils sont en haut ou il trouvent les coudees libres sestendent en sorte qu'ils donnent lieu a l'eau de descendre, quoy que cecy soit dit assez la coniquement". Vol.4, p.297).

[111] (Vol.4, p.53, 97, 111, 201).

[112] (Vol.4, p.239, 275).

[113] (Vol.4, p.150,174-5, 239).

[114] (Vol.4, p.98)

[115] (Lawrence ROOKE (1622-1662) was professor of astronomy at Gresham College, but had been at Oxford University before. In 1657 he was made professor of geometry. The organization was founded in his room and became the Royal Society after his death. He carried out experiments on collision and heat and oil in a tube. He also developed methods for maritime observations. Dictionary of Scientific Biography, Vol.11, New York, 1975).

[116] (Vol.4, p.297).

[117] (Vol.4, p.93).

[118] (Vol.10, p.119).

[119] (Stroup, 1981, p.147).

[120] (Vol.17, p.330-3; Vol.4, p.305).

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[121] (7th October 1662 and 26th February 1663. Vol.17, p.333. Stroup, 1981).
[122] (Stroup A., 1981, p.147).
[123] (Vol.17, pp.332-3).
[124] (Vol.17, p.319).
[125] (Vol. 4 p.320; Vol.17, p.333).
[126] (Vol.17, pp.324-9).
[127] ("il semble que cet air provenant de l'eau a un plus grand pouvoir de s'étendre que l'air ordinaire, car si l'on introduit dans A une bulle d'air de la grandeur de deux graines de chènevis l'eau ne descend que trés peu en-dessous du niveau où elle parvenait grace à la pression exercée sur elle par l'air provenu de l'eau qui occupait la moitié seulement du volume mentionné. Car sinon une double quantité d'air, la pression étant la meme, devrait se dilater deux fois plus". Vol.17, pp.328-9).
[128] (Vol. 17, pp.328-9).
[129] (Vol.4 p.334; Vol.6 p.586).
[130] (Vol.4 p.345; Vol.6, pp.58-7).
[131] (Vol. 4, p.365, 377).
[132] (Vol. 4, p.377, 433).
[133] (Vol. 4, p.482).
[134] (Vol.4, p.472).
[135] (Vol.4, p.366, 2nd July; p.377, 15th July; p.381, 20th July; p.385).
[136] (Vol.7, p.202).
[137] (Vol. 19, p.16, 189-207).
[138] (Vol.19, pp.201-6).
[139] (Vol. 19, p.192).
[140] ("eau rarefié par le feu" Vol.6, p.95).
[141] (Vol.6, pp.95-6).
[142] (Vol.19, p.239).
[143] (Vol.19, pp.207-212).
[144] (Vol.7, p.204).
[145] (Vol. 9, p.203).
[146] (Vol.9, p.421).
[147] (Middleton, 1964, p.92).
[148] (Vol. 7, pp.261-2. Design of Huygens' two liquid barometer in 1672).
[149] (Vol.7, pp.221-2).
[150] (Winter, J. "Ch.Huygens" in Les Inventeurs Célèbres, Lucien Mazenod, Paris 1962, p.47).
[151] (R.Hooke, Posthumous works, London 1705, p.365 "I saw an absolute necessity for a pressing fluid very much subtile than air, and yet consisting of parts of a determinate bulk").
[152] (Vol.9, p.421, 469).
[153] (Vol.7, p.204).
[154] (Vol.19, p.5; Vol.16 p.185 n.9; Vol.17, p.264 n.3-4; Vol.19, p.553).
[155] (Vol.19, p.5, 471).
[156] (Vol.4, p.150).
[157] ("l'hypothese des ressorts de l'air est fort ingenieuse et satisffait a la pluspart des phenomenes, il n'y a que cettuicy que je nescay comment on y pourroit rapporter a comprimè dans un vase retient sa fluiditè. Car quand on s'imagine ce vase plein de tels ressorts touchant les uns les autres". Vol. 4, p.172).
[158] ("Mais je scay qu'il ne done cette hypothese que comme un project, et principalement pour apporter un moyen possible de l'expansion de l'air", Vol. 4, p.172).
[159] ("La force de son ressort suit la proportion contraire des espaces ou il est reduit", Vol 4, p.171).
[160] (Against F. Linus, London 1662).
[161] (Vol.4, pp.176-8).
[162] (Vol. 4, pp.197-8, 201-2, formula, pp.205-6).
[163] (Vol. 4, p.217).

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[164] (Vol.4, p.217-220).
[165] (Vol.4, p.220).
[166] (Hesse, M. Hooke's Vibration Theory and Isochrony of Springs, ISIS, 1966, Vol.57, 4, N.190, pp.433-441).
[167] (Vol.4, pp.221-2).
[168] (Vol.4, p.222).
[169] (Vol.4, p.275).
[170] (R. Hooke, Posthumous works, London, 1705, pp.365-6).
[171] (Vol.4, pp.432-3).
[172] (Vol.4, p.428).
[173] ("miro modo ab alia aliqua se sustentari, quam externi Aeris pressione". He continued: "Quousque provehere porro Experimentum hoc possimus, melius, procuratis, Tubis longioribus conjicimus, dummodo ullos nacisci possimus fatis longos, qui summe possibilem. Mercurii suspensionem nobis ostendant". Nov.1663, Boyle to Huygens, Vol.4 p.44).

[174] (Vol.19, p.215).
[175] (Vol.3, p.439).
[176] (Vol.19, pp.214-5).
[177] (Vol. 19, pp.217, 219).
[178] (Vol. 19, p.217).
[179] (Vol. 19 p.216).
[180] (Vol.7, pp.201-206; Vol. 17 p.263).
[181] (Vol.19, pp.217-8).
[182] (Vol.17, p.306).
[183] (S.Shapin, 1994, p.363).
[184] (Shapin, 1994, p.126)
[185] (Papin's book, Chapters III-VII; Vol.19, p.224).
[186] (Vol.19, pp.224-238).
[187] (Vol.8, p.198).
[188] (Vol.8, pp.172-4).
[189] (Pacey, 1980, p.126).
[190] (Pacey, 1980, p.125).
[191] (Pacey, 1980, p.125).
[192] (Talbot and Pacey, Antecedents of Thermodynamics in the work of Guillaume Amontons, Centaurus, 16, 1971, p.26).
[193] (Vol.9, pp.78-9).
[194] (Vol.19, pp.216-248).
[195] (Shapin, 1988).
[196] (Hunter, M. in: Establishing New Science, 1989).
[197] (Daumas, 1953, p.130).
[198] (Middleton, 1964, p.83, 99, 366, Mariotte, Essay du Chaud et du Froid, Paris, 1679).
[199] (Vol. 7, pp.261-2).
[200] (Talbot & Pacey, 1971, p.21).
[201] (Vol.9, p.434, p.465, 481. Some of these letters were sometimes delivered by Papin's cousin, J.Gousset, Vol.9, p.488).
[202] (Hooke, R, Posthumous works, London 1705, p.3).
[203] (Hooke, Posthumous works, 1705, pp.126, 155, 573, 286)
[204] (Vol.5, p.345).
[205] (Henry, J. "Robert Hooke, the Incongrous Mechanist, in Hunter and Schaffer edit. Robert Hooke. New Studies, the Boydell Press, 1989, pp.181-206).
[206] (Vol. 4, p.84, 92).
[207] (Vol.4, p.113).
[208] (Statics, Vol.19, pp.23-75; dynamics, Vol.19, pp.95-175. Pesanteur, Vol.21, pp.377-382. Discours de la Cause de la Pesanteur, Vol.21, pp.443-499).

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[209] (Stroup A, 1981, p.137).

[210] (J.Henry, Matter in Motion, PhD, OU, 1983).

[211] (Middleton, 1965, p.145).

[212] (Birch, T, edit. The works of the Hon.R.Boyle ... A new edition, 1744, Vol.1, p.114).

[213] (Vol.7, pp.204-6).

[214] (Middleton, 1964, p.80, & History of the Academy Royal of Sciences. Paris 1733, Vol.I, pp.270-8).

CHAPTER 3

HUYGENS' THEORIES OF MOTION, MATTER AND COSMOLOGY (from 1661 to 1690s).

The aim of this chapter is twofold. First, Huygens' studies on 'physics' are presented. They became essential as the theoretical mechanics, which accompanied Huygens' inventions and machines. Second, the variety of his work as a natural scientist is shown further in his theory of matter and cosmology. It brings support for the interpretation that Huygens broke away from traditional philosophy and started to develop a mechanically-based tradition.

Huygens' laws of motion were the basis of all his mechanical and physical works. He worked on rectilinear motion and then applied it to circular motion. His observations with the air-pump induced the development of different theories in statics and dynamics, breaking away from the traditional and metaphysical definitions of nature. Also in astronomy, Huygens deduced a cosmology where he imagined other beings living in an 'infinity of worlds'.

Huygens began to doubt Descartes' theory of impact in 1652, seven years after he had begun studying at Leyden. One of his tutors, Frans Van Schooten, was a pioneer in the teaching of Cartesian philosophy at the university, against the wishes of more traditional tutors and he edited some works by the French philosopher[1]. Furthermore, Descartes was a friend of Constantijn, Christaan's father. But already by the early 1650s Huygens was refuting these laws. He wrote different treatises on the subject during the 1650s and also in the late 1660s[2]. He used the same

Cartesian law's to prove that they could not stand, as Descartes had described them, neither theoretically, nor by experience[3]. He presented his results on the impact of bodies in De Motu Corporum of 1656 and on which he had been working since 1652. In 1657, Huygens had invented the pendulum clock and worked on it, not only experimentally, but also theoretically deducing the first mechanical compendium to explain how an automaton worked. He studied the relative circular motion of bodies and the *vis centrifuga*, as well as cycloids.

Uniform and circular motions, the experiments with the clock and Archimedean geometry were easy compared to finding a law to explain the motion of particles that made up the different elements in nature. This was a new field of science, still developing. When Huygens was working on the air-pump between 1661 and 1663, he observed phenomena, which could not be explained with the geometrical ratios deduced for the clock. His experiment of the void within the void challenged him to develop a new theory of matter. The physical properties of matter proved to be elusive for some years. Huygens took into account the size of particles (*corpuscules*) which were bigger the coarser the element was. Earth was made up of bigger particles, those of water were smaller, and those of air smaller still. Subtle matter was more elusive. It had to be made up of particles too, but they had to be smaller than those of air and able to penetrate anything, from other natural elements to glass. Subtle matter developed as an appropriate step to explain the unusual and unexpected phenomena in the void within the void. He defined an even thinner matter. According to Huygens the cause of pesanteur was a subtle matter made up of extremely small particles.

By 1668, Huygens had developed his theory of matter. In general, an arithmetical notation could describe statics and dynamics. Physical laws were necessary to define the phenomena observed in nature. The deduction of the universal laws of motion and gravity was left to Newton. Huygens was convinced that there was no need of a God to explain these phenomena either; his philosophy did not have a metaphysical base. His theories were developed independently of God's existence or intervention. He also had his own concept of relative motion and space.

The basic principle of relativity of a body in motion, in a system itself mobile, was at the base of most of Huygens' works since 1656, when he must have finished De Motu Corporum. From this, he went on to study the motion of bodies on the surface of the earth itself rotating on its own axis. One of Huygens' greatest achievements was to deduce the value of gravity, but he could not understand gravity as attraction of bodies at a distance and did not agree with Newton's definition in his Principia of 1687. However, he influenced Newton's definition of centrifugal force. Huygens did not define centripetal force, this Newton did. Although the work on the principle of relative motion was essential and useful in all his theorems he did, however, not believe in absolute space[4]. Towards the end of his life, the philosophy of particles proved useful to explain the propagation of light. Finally, he described a cosmology where life could exist in other planets of the universe.

1. UNIFORM RECTILINEAR MOTION. De Motu Corporum (1652-56).

Huygens recognized the influence Cartesianism had had upon him during his youth. This was expressed in his last works[5]. However, he did not follow it closely. One of the most important early works, with which he proved Descartes wrong was De Motu Corporum, completed in 1656[6]. He wrote some of it in 1652, and added propositions in 1654. Although well known to his contemporaries, it was published only posthumously (1703). Was this because of Van Schooten's advice not to publish? Van Schooten wrote to Huygens to give up his studies on the impact of bodies, because Descartes' new philosophy was becoming increasingly accepted[7]. Huygens replied that Van Schooten would change his mind if he read his refutation of the Cartesian laws of impact[8]. Van Schooten also mentioned the edition of a work by Descartes that he had published[9].

From 1652 until he completed the treatise in 1656, and then until 1664, Huygens worked out different propositions on the impact of hard bodies[10]. Although he had deduced the principle of conservation of forces by 1652, he did not say how he had obtained it when he used it on the relation between vertical and horizontal motion. He made several calculations for the principle of the conservation of the quantity of motion: mv^2 [11], which for Huygens was only a number[12]. During 1654 the principle of relativity of motion was deduced; bodies moved in a space itself in motion, for example, a moving boat in the river[13].

De Motu was based on the concept of inertia, on the symmetry of two equal bodies with opposite velocities and the principle of relativity[14]. It began with three hypotheses[15]. The third hypothesis was important for

Huygens' concept of relativity of uniform rectilinear motion. This hypothesis took into account bodies in motion from rest within a system, itself moving. The example given was used in later demonstrations of relativity of circular motion too. Two bodies were made to collide at the same velocity while an observer on a boat -the moving system- studied them. They did move away after impact with the same velocity. With respect to the navigator, the same would happen if the impact had occurred with the boat at rest or on land. This hypothesis referred to hard bodies of equal size and speed[16]. But other hypotheses concerned bodies of different sizes[17]. The laws of impact appeared in his letters as he progressively found a new hypothesis against each of the Cartesian laws[18]. This was "the first comprehensive account of perfectly elastic bodies"[19].

However, Huygens kept the Cartesian concept, still used in dynamics, that quantity of motion before and after impact should be the same[20]. Relativity was fully used on the new propositions on collision. In 1652, Huygens studied the impact of two bodies where the space and observer were considered immobile. If two bodies collided at different speeds, they moved away (V'a and V'b) with the same relative velocity (Va and Vb). By means of geometry he arrived at the same result as with modern algebra[21]. He deduced geometrically the complete solution of the direct impact of hard bodies[22]. In the last proposition of the treatise, he studied a system of more than two bodies, and changed their size and velocity[23]. Several propositions followed where he changed different factors: the speed[24], the amount of motion[25], the size of the colliding bodies[26], or both speed and size[27]. In his experiments Huygens tried to find a way of converting horizontal speed into vertical speed and vice versa[28], and also worked on the reversibility of impact[29]. After impact the quantity of motion of two colliding bodies was given by the formula: $m_A v_A^2 + m_B v_B^2 = m'_A v'_A^2 + m'_B v'_B^2$. At this point, m was still equivalent to the Cartesian: *Grandeur* of bodies. It was defined as mass in *De Vis Centrifuga.*

To this Huygens added the indirect or oblique impact of bodies[30], and the more general problem of the direct impact of hard bodies[31]. Between 1656 and 1667, Huygens worked on different theorems and propositions for the De Motu[32]. Although, he had deduced all the propositions of this treatise by 1656, he still improved them over the years and communicated with contemporaries about them, Van Schooten in 1652[33], Kinner à Löwenthurn in 1653-54[34], and Mylon in 1656[35]. Between 1657 and 1658, and in his correspondence with Sluse, Huygens discussed the foundations of his laws of motion[36]. Sluse was not totally convinced by these propositions on impact[37]. Huygens did not take his criticism lightly, in his answer, he said that Van Schooten had tried to dissuade him from publishing the treatise because it was so anti-Cartesian[38]. He presented the experiments he had carried out to refute Descartes and the two main principles of the treatise[39]. Huygens added that if Sluse agreed with the hypotheses enclosed, then it would be easier for him to accept the others. In 1659, after reading the treatise, Sluse wrote to Huygens urging him to publish his theories[40].

Huygens made instruments accompanied by drawings to measure the velocity of bodies in free fall. He defined them as Instruments to measure the space traveled by a body in free fall in one second In 1659, Huygens must have built a model because he carried out some simple tests to find the space traveled by a body in free fall in one second and registered them. Once more he showed that he was an engineer, in this case designing instruments to find and prove with simple mechanical experiments the velocity of bodies in free fall.

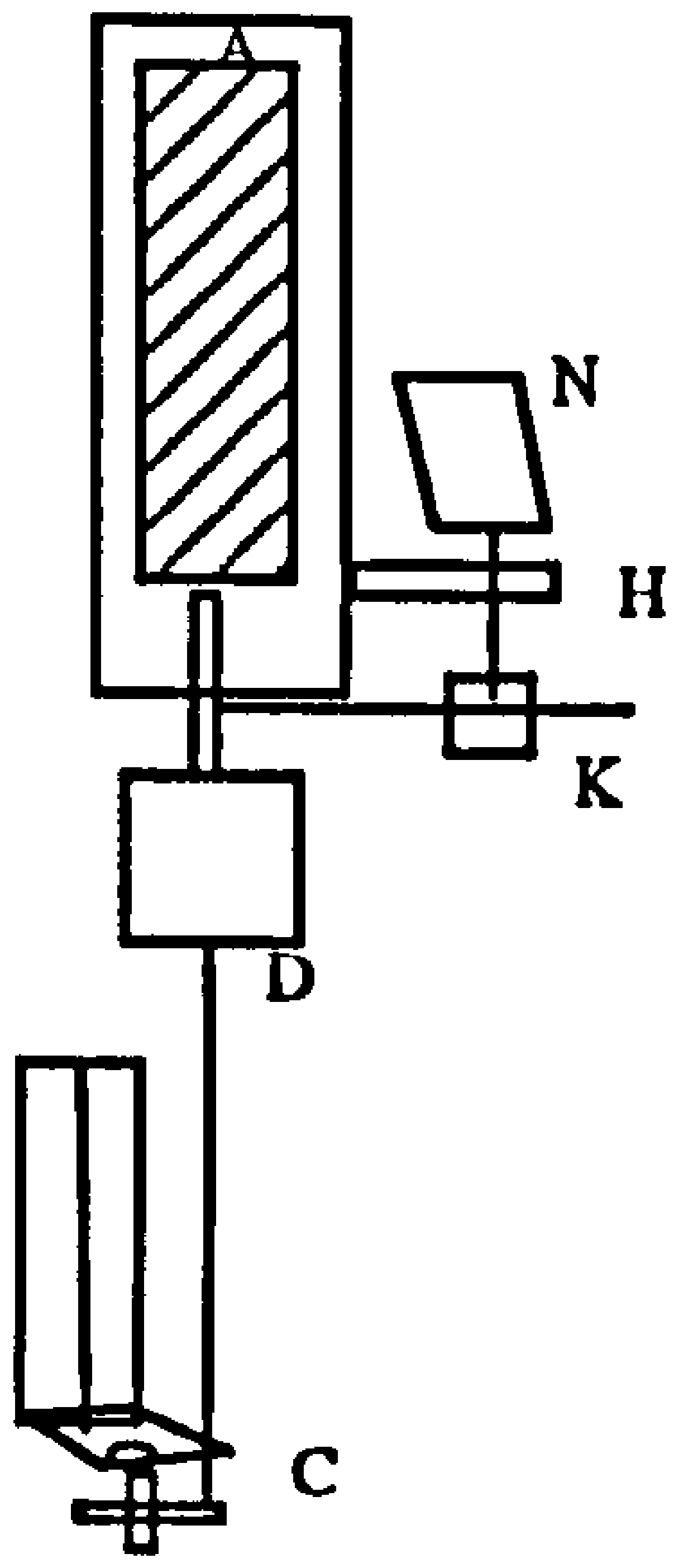

Figure 1 - Instrument from 1664 to find the measure of the space traveled by a body in free fall in one second[41].

In figure 1, a weight D fell to C when the NHK system was operated[42]. Huygens said to Moray that he knew that Hooke had made a small machine to measure the speed of descending bodies. However, Huygens had not seen it because Hooke did not send him any designs.

At the end of 1660 Huygens was in France and he discussed his theory of motion with Azout and, a few months later, during his visit to England, with some English natural philosophers[43]. Some experiments on collision were performed at the Royal Society in 1666[44]. In 1668, Wallis[45], Wren[46], and, in 1669 Huygens[47], were invited to present their theories of impact. Huygens sent a letter with a summary of these laws, Oldenburg decided to publish it, but Huygens had not given his consent. Huygens' article had been published in France in March and he did not like Oldenburg's initiative[48]. This correspondence forced Oldenburg to defend himself against Huygens' accusations of injustice[49]. Finally, Huygens was satisfied with the letters he received from Oldenburg and with the article published in the "Transactions"[50]. He then presented the extract of his letter to the editor and a summary of the laws of impact as well as the article that had been published in the Journal des Sçavans[51], including his theory on the spring of the air[52] and water.

Huygens defined the physical properties of air and water based on the properties of size and compressibility of their particles. The spring of air was explained as air particles moving in all directions and in circles around their centre. According to Huygens they moved like that because of the rapid motion of the subtle matter. When the space occupied by air was reduced, they hit each other and moved away. The liquidity of air required a certain kind of spring, but when the air was compressed in a tube it did not present such liquidity. Water also had liquidity. It was the subtle matter contained in it that gave the water its motion. Unlike air, water did not compress as well as air when the space it occupied was reduced, because the particles of water stood one above the other, whereas those of air fluttered about, in a random manner[53].

These conclusions were linked to Huygens' concept of matter. He extended the impact of bodies to the motion of atoms that formed everything. Notice that he did not speak of vortices as Descartes did, but of a motion closer to free atoms which could be compressed or expanded if space was reduced or increased. Atoms could impact with each other and they moved around their own centres in the space they occupied but not in regular vortices.

2. CIRCULAR MOTION. De Vi Centrifuga (1658).

Centrifugal force was defined in this treatise as a radial force, which is the measure of its tendency to recede from the centre. Therefore, a body moving in a circle would tend to follow the line that links it to the centre. It is a radial force (see text in figure 2, footnotes and Gabbey, 1980). In the De Vis Centrifuga, Huygens reflected his interest in absolute motion and the nature of centrifugal force that caused the flattening of the earth and the variation of gravity on its surface. Huygens wrote it in 1659 to oppose Descartes' theory of motion. The same year he tried to explain terrestrial gravitation[54]. The treatise summarized some of the main propositions, which had appeared in his Horologium Oscillatorium. Once Huygens had created the pendulum clock, he had to define the way it worked. Geometry allowed him to study the nature of circular motion thoroughly. He defined isochrony and many other properties of cycloids, paraboles, evolutes and other curves.

Huygens began this treatise with a preface that included the relationship between a body falling through an inclined plane and free fall. He stated that because gravity was the tendency to fall, then heavy bodies, or better, bodies 'with weight', which fell along inclined planes would move with such an acceleration that, in equal times, equal speeds would adjust to the speed acquired. These results matched with experience: the different spaces covered by bodies from rest were in a ratio with the squares of the time[55]. Furthermore, if the resistance of air could be disregarded, this law would also apply to much bigger spaces. In this he acknowledged the influence of Galileo and Riccioli[56].

In order to prove this law Huygens experimented with bodies suspended from cords, and with others linked to a suspended body falling along an inclined plane. Huygens tried to prove the relativity of circular motion with the experiment of the man in a moving wheel. In such a wheel the man held a body suspended from a cord[57]. In all the experiments of this kind the hand which held the suspended body felt a vertical traction in the hand itself. Secondly, it was parallel to the inclined plane and, thirdly, if the cord was cut, at that point, it would follow a line tangent to the radius of the circle of the wheel[58]. This traction would be just before the body was liberated and the subject would experience a pull from the body trying to move away from the circle. However, the force felt in the centre of the circle trying to flee away from the cord that held it would keep the body moving circularly (see figure 2 in footnote)[59]. This tendency of the body to move away from the circle was compared to suspended bodies descending. All heavy bodies tended to fall with the same speed and with an identical accelerated motion. But this force increased as the body became larger, and it was the same for the same size of body whatever the type of cord was used to suspend it. However, the tendency to move away from the centre would increase if the wheel turned faster and would diminish if it turned at a slower speed. The factors of speed and body size were changed and studied in the first four propositions to further clarify the concept of centrifugal force[60]. These propositions were useful when studying a suspended pendulum and the tension exercised due to the centrifugal force[61]. They also helped to define conical pendulums[62]. Huygens continued with the geometrical method to define centrifugal force and the value of g because he did not have the arithmetical notation used nowadays: $F = mv^2/r$.

Although Huygens had written De Vis Centrifuga by 1659, it was not published during his life but posthumously, in 1703. However, its content was well known to the scientific community of the time. Some of the propositions of this treatise appeared in 1673 in the Horologium Oscillatorium. Huygens' interest in centrifugal force was a consequence, not only of tradition, but also of his need to find an explanation and formula for the circular motion of the pendulum. He continued studying centrifugal force for the rest of his life. Unsatisfied with a simple mathematical account on paper, in 1668[63], Huygens showed his skills as an engineer by creating a machine, yet another mechanical instrument, to measure centrifugal force. The instrument consisted of a 12 French inches pole with three arms in the form of a quarter of a circle, joined together in the centre, separated at the same distance from each other and placed on top of a pole (see figure 3). With this instrument, he tried to find the physical proof of how bodies in circular motion tended to move away from the centre, which he had called centrifugal force.

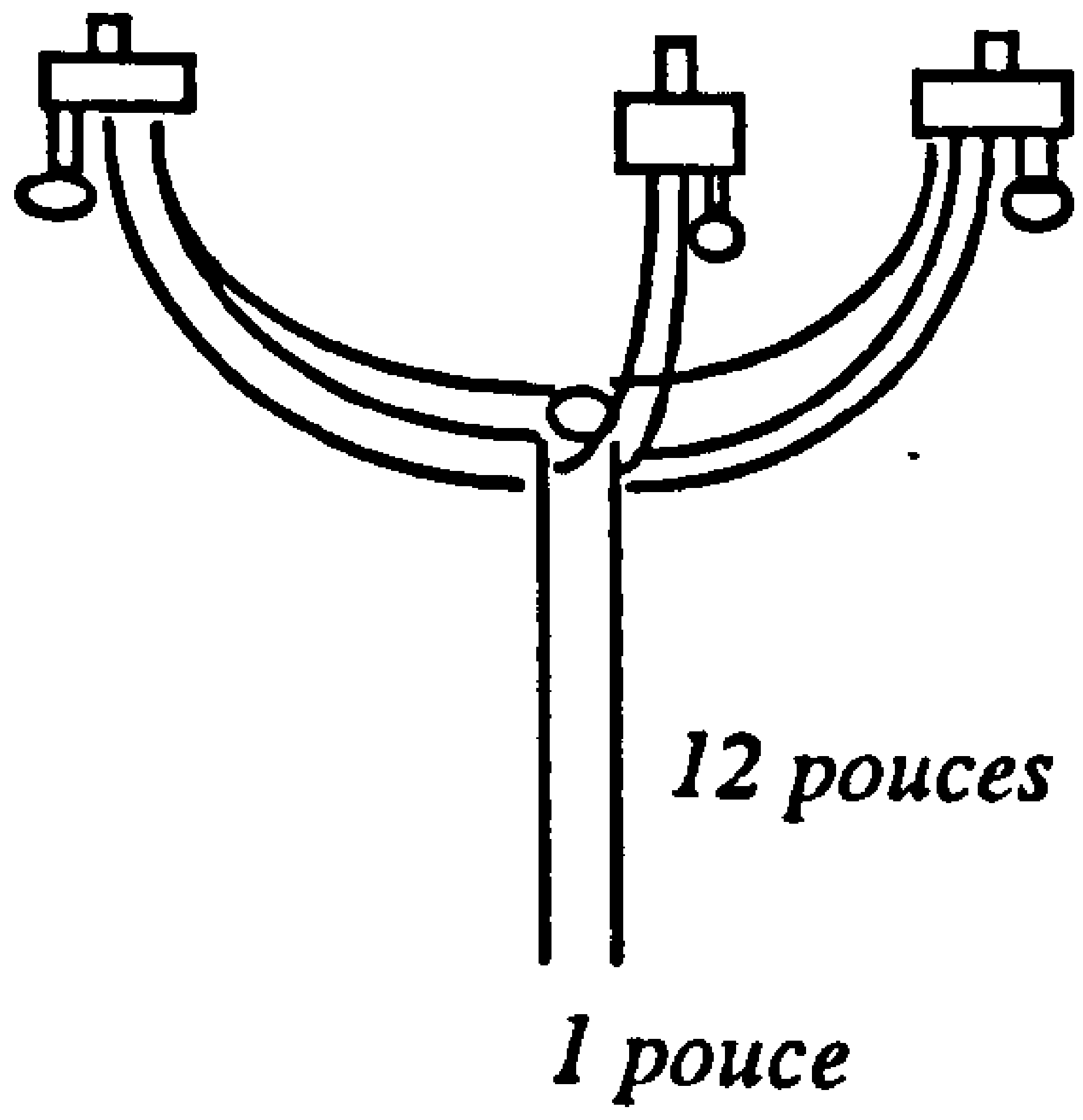

Figure - 3 - Instrument to measure centrifugal force.

In figure 3, the distance between the arcs at the top was 10 *pouces*, or French inches. Huygens designed it in 1668, but it is not certain whether he made the design in February or July. Huygens experimented with this instrument because he said so in the Discours de la Cause de la Pesanteur and in correspondence with his brother, Constantijn[64]. On August 1669, Huygens demonstrated to the assembly of the Academy how circular motion generated centrifugal force.

From 1659 until 1666, Huygens worked on this instrument and on several prefaces to the De Vis Centrifuga. He continued this work well into the 1690s[65] after Newton's Principia, which influenced some of his hypotheses. He also worked on the centrifugal force on the surface of the sun and the planet Jupiter and compared the gravity on their surfaces. Huygens attributed the invalidity of the measurements of longitude carried out on the trip of 1686-7 to an important factor. The centrifugal force created by the rotation of the earth had not been taken into account[66]. However, later in his life, after developing his theory of relativity of motion further, he did not think along the same lines. He did not believe that there was a centrifugal force due to the rotation of the earth, but a specific angular speed[67]. This he stated in the posthumous treatise the Cosmotheoros, published in 1695[68].

In 1690 Huygens summarized his research on motion in one of the draft prefaces to De Motu and De Vis Centrifuga. He intended to write a common introduction to these treatises as some drafts of 1689 and 1690 show[69]. He used geometry, in the free fall of bodies, in the properties of the cycloidal curves, the pendulum, and the centres of oscillation and in circular motion. On his work on impact, he commented on the influence of some works by Galileo, Descartes and Mousnerius. He also mentioned the presentation of the laws of impact to the Royal Society together with Wallis and Wren, and once more he commented on Oldenburgh's injustice[70]. Other prefaces referred mainly to motion, such as absolute motion. He wrote several prefaces to this treatise and to different manuscripts of unknown date[71] in his attempt to introduce the subject in the clearest possible way to the reader.

In 1692, Huygens wanted to publish some demonstrations of impact[72] and continued his work on absolute motion. He also worked on the Copernican system[73]. The correspondence of 1694 presents Leibniz's comments on Newton's circular motion and Huygens' relative and absolute motions[74]. Huygens was surprised at Leibniz's good memory because he had worked on these issues twenty years earlier[75].

3. TREATISES ON STATICS, DYNAMICS, *PESANTEUR* [76]: AN ATTEMPT TO EXPLAIN THE PHYSICAL PROPERTIES OF MATTER AND MOTION.

Huygens knew very early of Descartes' theories because, like Mersenne, Descartes was also a good friend of his father, Constantijn. For Descartes the essential characteristics of matter were its extension and motion. Matter was formed of small particles, which filled space, and they were increasingly smaller. For instance, the solid earth was made up of bigger particles than liquids and these in turn were bigger than air[77].

Huygens had met the great mathematician Gassendi in 1655, the year he died. That year Huygens wrote to his father Constantijn from Paris[78] expressing sorrow over Gassendi's death[79]. Gassendi had been a great admirer of Huygens' work, as some contemporaries knew[80], and had translated the works of Epicurus and Lucretius. His theory of matter was based on atomism. Later on, Huygens quoted him in his correspondence[81] and continued looking for Gassendian works, which he tried to obtain from French colleagues or from those acting as secretaries or who liaised with scientific organizations[82]. In England, Charleton[83], a physician who used to present his work at the Royal Society[84], disseminated Atomism and Gassendi's theories. Hooke, following Epicurus, wrote to Huygens about air particles moving circularly[85].

Gassendi[86] explained all natural phenomena in terms of atoms and their motions in the void[87]. All the elements were formed of atoms. Democritus had further developed the atomism theory of Leucippus of Miletus stating that only atoms and the void were real. The atoms were infinite in number and occupied an infinite void. They were in continuous motion and colliding then rebounding, or joined together, thus forming different compounds. The physical properties of the atoms were indivisibility, indestructibility and that they could not be generated. They were homogeneous and solid. These atoms could move because void existed where they moved[88]. Huygens, followed atomism more than Gassendi, who found this theory very useful but non-religious in other parts, as it will be explained later.

Some contemporaries like Boyle also believed in atoms and the void. Boyle accepted the definition of the void given by Epicurus, Democritus and Lucretius, as a place with no corporeal substance[89]. He held them as authorities on the subject and he also was influenced by Cartesianism[90]. Reference to Descartes is found in his correspondence with Huygens (see chapter 2). Shaffer and Shapin say that Boyle treated Hobbes and Descartes together[91]. Therefore, Descartes' work was known to Boyle. Unlike Epicurus, Boyle believed in God as the Creator of the universe, who had set in motion the *prima materia* existent as extended

(Cartesian), divisible and impenetrable, formed of particles/corpuscles which could only be divided in the mind or by God but not by nature. He believed that matter and motion were at the root of all physical phenomena[92].

In 1661 and 1662 Huygens did not know how the phenomena observed in the void during the void experiments had originated. He attributed the causes to a certain subtle matter. In 1668 he developed a definition of it together with his theory of motion and his studies on atomism in particular. He was applying the impact of bodies to the elastic particles, which made up the material universe. These particles were spherical and of a perfect hardness[93]. They surrounded all the planets in the universe and, unlike Descartes' matter, which could only move in rectilinear motion and in vortices[94], they could also move in a circular motion. This he used to explain the observed phenomena in the air-pump and, later on, to define the universe and what it might be made of. He asked what caused the second bubble to form and searched for the answer within the philosophies he knew. He found it, partly in Descartes, but in particular, in Democritus and in Gassendi, and therefore, in Lucretius and Epicurus. To them he attached his own ideas and developed his theory of matter. He dedicated a good deal of his time to the study of the physical properties that made up the natural elements and their motion. He aimed at explaining not only the physical properties of the results observed with the air-pump, but also how they related to each other in the space where they moved. These were developed further to explain matter and motion in the whole universe, where the centrifugal force and weight/gravity, or pesanteur, were the key issues. With this purpose in mind, he wrote two treatises, one on statics and another on dynamics.

3.1. Works on statics and dynamics from 1668 to the 70s

Huygens' work on statics[95] and dynamics began in 1659. In dynamics, he worked on the free fall of spheres of different weights; and on the isochronism of cycloidal falls[96], as well as the calculation of the length of the isochronous pendulum for different oscillating bodies, lines, planes and solids[97]. He also worked on centres of gravity[98]. By 1668, he had already developed a statics and dynamics that could explain the phenomena observed in the experiments with the air-pump. His main work on statics was completed between 1668 and the 70s. He had been questioning the properties of bodies in motion and how they related to their environment since 1658. He studied the inclined plane, pulleys, velocity, toothed wheels (geared wheels) for lifting weights, the speed of air, the force of moving water, the force of springs, the resistance of bodies, pumps, the statics of floating bodies, centres of gravity, the resistance of bodies to fracture[99], the universal measure[100], the centres of agitation of suspended bodies, the motion of pendulums and the fall of bodies. He also studied the construction of various machines for craftsmen: carpenters, turners, polishers, stone masons, weavers[101]. Huygens showed the applicability of his work to real life and for that he used forces in motion as the basic system upon which to build his mechanics. The list given above shows the extent of his interests and his influence at the time as an engineer.

Huygens followed the same method throughout. First, he thought of a hypothesis, then, he deduced the appropriate theory and performed the necessary experiments to test it. Finally, he tried to find a common law governing the forces, which moved all this craft, machinery. He searched for and created something basic and useful for craftsmen who needed a mechanically driven machine in their work. He used Archimedean propositions for the study of mechanical forces and the resistance of bodies to fracture. One system of forces he deduced in 1676 consisted of toothed wheels and toothed axes (or wormdrive as it is known now) which imparted more speed with less motion compared to other systems (see figure 4).

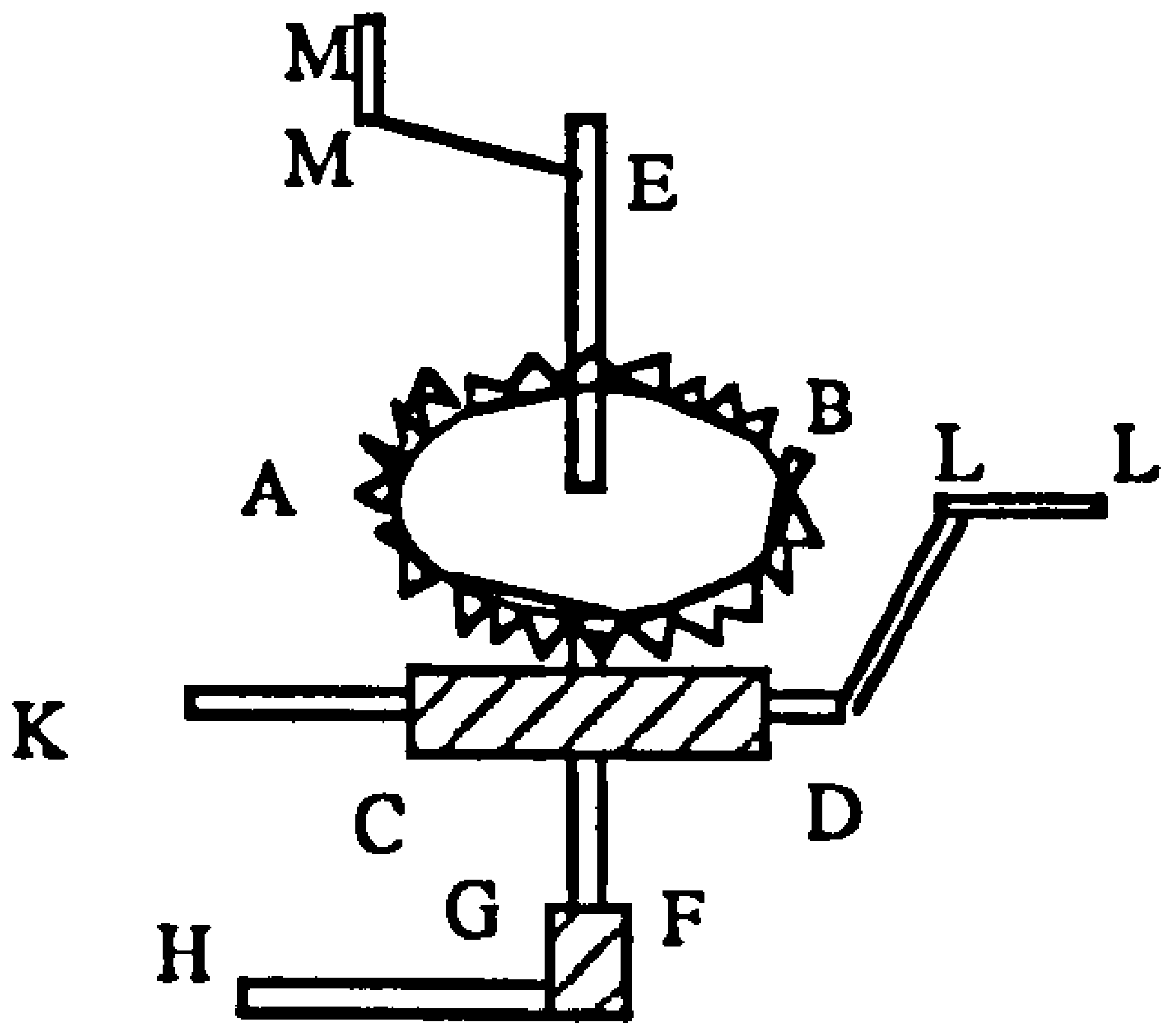

Figure 4 - System of a toothed wheel and toothed axis, or wormdrive, to describe the forces driving basic mechanical machines.

This drawing and the way Huygens understood it are yet one more example of an engineer designing and explaining a system of forces basic to the technology of various crafts. The wormdrive CD was set in motion with handle LLK. This axes, in turn, moved wheel AB that then moved axes EF to which MM and cord GH were attached, setting them both in motion. It is well known these days that this system would multiply the impulse from handle LLK, as determined by Huygens. This mechanical system of wheel and axis could be used to lift a lot of weight[102], and to keep in motion other basic machines.

Another statics system used to lift weights was a classical and traditional one. The body falling along an inclined plane was better known and

Huygens studied it in detail. He described the equilibrium of forces between pulleys and that of the balance[103]. For the latter, Huygens, once more, resorted to Archimedean propositions that he largely expanded. And, finally, he studied the statics of cannon[104].

In dynamics, Huygens studied the speed of bodies, forces and the resistance they encountered when in motion He applied them to the simple pendulum and the fall of bodies. He also deduced geometrical ratios for bodies moving in different media, such as air and water and how they related to vertical motion upwards and downwards in these media[105]. His geometrical explanation included the division in very small parts of the distance covered by the body and compared the small squares formed to find the right ratios of spaces traversed and the time employed[106]. Later on, he tried to measure the resistance suffered by bodies in water. He designed several systems, such as that of a piece of wood cut in the shape of a parallelogram attached to a cord going over a pulley with a weight hanging at the end of it. Huygens measured the vibration on this cord to find the resistance of bodies in water (figure 5).

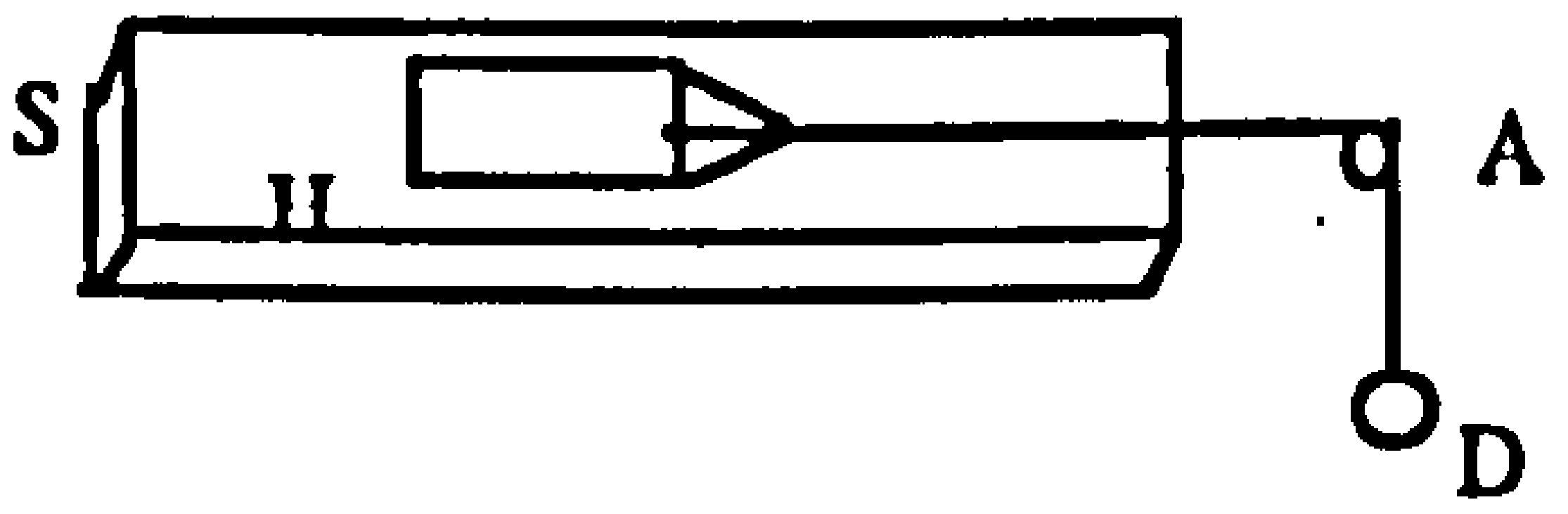

Figure 5- The parallelogram attached to the cord with a weight D at the end of it was used to measure the resistance encountered by bodies on the water.

The parallelogram floated in a big container filled with water. The weight D was observed to vibrate and also the parallelogram; the vibrations were counted, at both ends. He found that the number of vibrations in D almost doubled those felt in the parallelogram and he concluded that if the speed of the parallelogram was double, that of the weight was quadruple. Therefore, the impression of the water against the same surface was in direct ratio to the square of its velocity. Huygens submitted these experiments to the Academy on April 1669. In this presentation he concluded that the velocities of a body were in direct ratio to the double weight which pulled it in the water. And the force of the weight D was equal to the resistance encountered by it in the water. Therefore, these forces counterbalanced each other[107].

The other medium in which Huygens wanted to measure resistance of bodies in motion was air. He drew machines to measure it. The drawing was presented to the Academy in 1669. In the title of this drawing the Academy designated Huygens as the inventor[108]. Therefore, he must have been the first one, at that time, to make this type of machine.

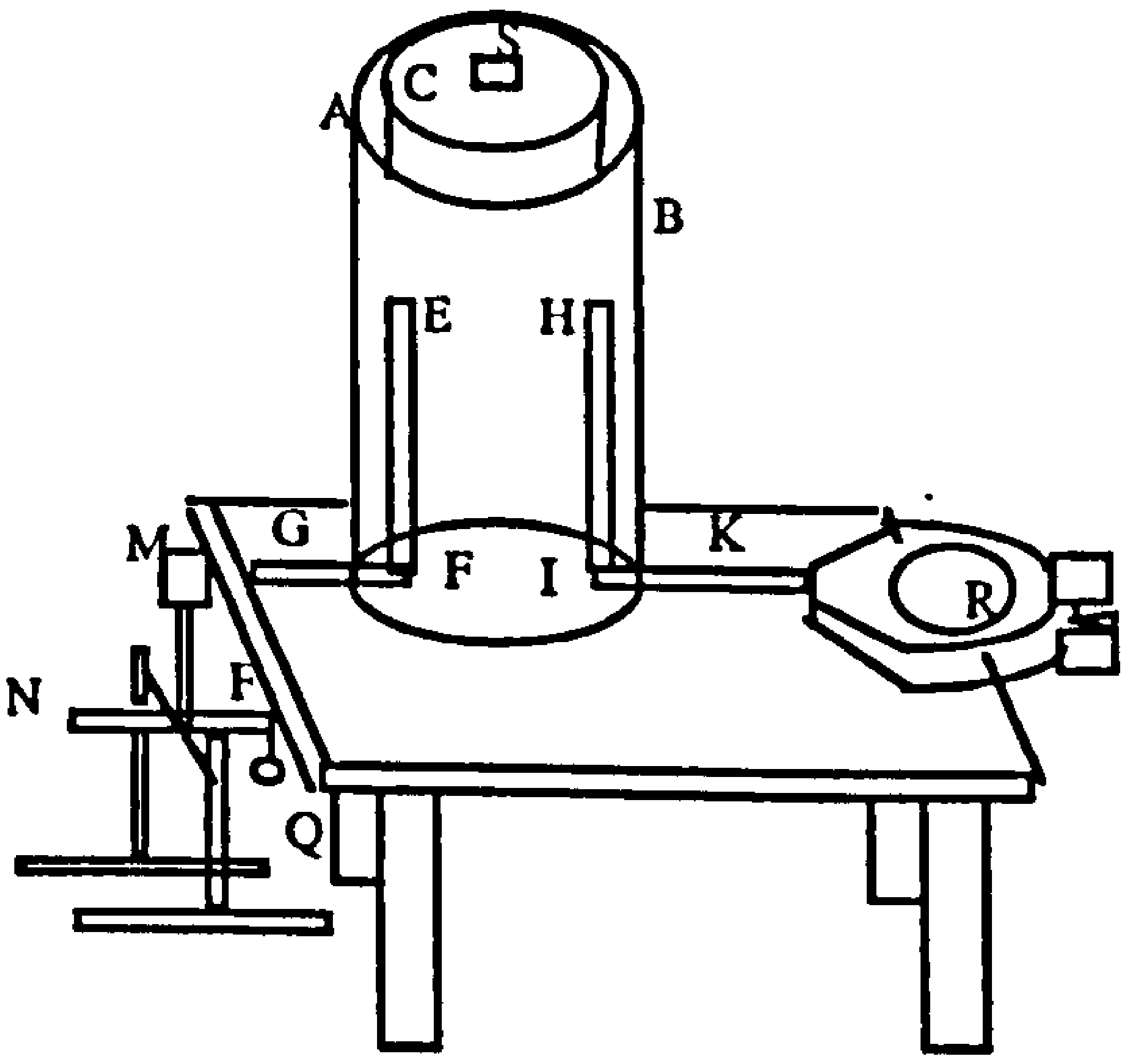

Figure 6 - Machine to measure the velocity of air.

This machine consisted of a big cylinder AB filled 2/3 of its height with water. Another cylinder C was introduced in AB with space all around it. The bellows (*soufflet*) R were used to introduce air in the cylinder. The air came out through EFG after placing a weight on top of cylinder C. The air from G moved the arm M of winch (*moulinet*) MNF. It was possible to know the changing force of the air when different weights were placed on the cylinder. Also the opening G could be varied in known proportions yielding different velocities of air. These Huygens recorded for various pressures from the different weights used. For example, for a weight of 44 French pounds pressing on the cylinder C, the weight which sustained the air was 12 1/2 grains, the time elapsed was 35 seconds and the proportion of the speed was 100. By calculating different speeds he concluded that these were in indirect ratio to the time. The pressures of air from R and those of the water were in a double ratio to the velocity. He also found that the pressure created on the cylinder was on a double ratio to the velocity, for air and water alike[109].

This was a mechanical device only designed to measure the speed of air in motion, but not air as made up of particles. The design resembles those made by engineers in later centuries. The different drawings[110] and the methodological record of the results suggest that Huygens performed experiments with this machine and must have made it himself. I have found no records of craftsmen making this instrument for him.

Between May and June, Huygens invented another machine to measure the velocity and force of air (see figure 7). This small device had a copper balance AB, equal to CD and a surface DE. The balance was kept in equilibrium, when the air blew against surface DE, the weight F marked the force of the wind. This instrument was easy to make and Huygens must also have built it himself.

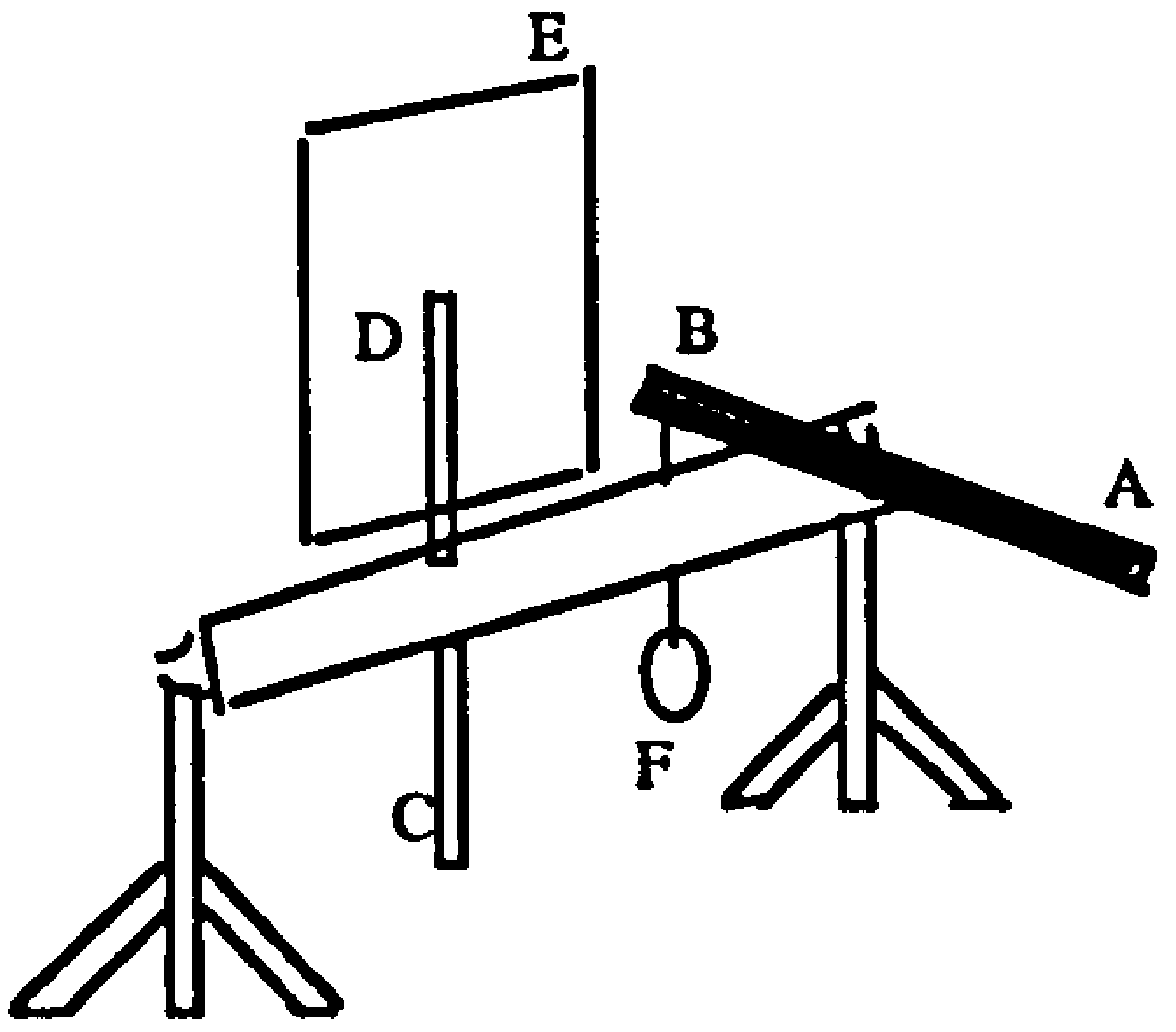

Figure 7. Device to measure the force and velocity of air (1669)[111].

The following month, June 1669, Huygens designed yet another machine to measure the velocity of air. It consisted of two wheels A and B, one of double diameter than the other and moved with a handle over an axis parallel to the ground (see figure 8). This time the air was detected by a sheet of paper on a frame CD held by another frame as its base DH and situated in front of the wheels. Another mobile frame FE was attached to the base at an angle of 45 degrees with a small pierced bob of lead hanging from it. With this apparatus Huygens measured the velocity of air according to the oscillations described by the bob when the wheels produced air. The utility of his studies on the *force mouvante*, as Huygens called the force produced, of water and of air were discussed in the Academy in July of the same year.

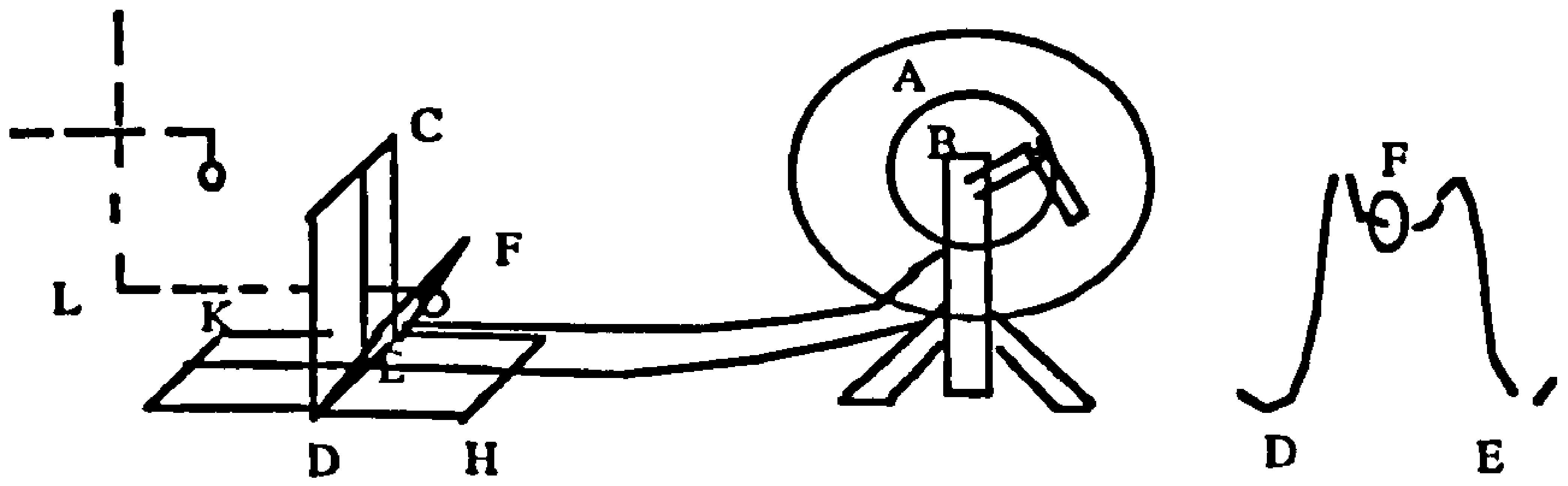

Figure 8 - Apparatus to measure the velocity of air [112].

Huygens noticed how important these studies could be because of their utility in those professions where air and water were used to move machines. This was the case of water- and windmills[113]. He then explained geometrically the resistance encountered by bodies on air and on water. The last demonstrations seem more a work of calculus than of geometry[114]. Smeaton performed similar experiments in the 18th century.

He also studied the tension felt by a cord holding a body on an inclined plane, as well as impact, or the conservation of forces. With geometry he explained the Torricellian tubes in a treatise on hydrodynamics. In it Huygens stated that the length of the tubes used did not influence the pressure on the foot of the tube, but that the height of the water contained in the tube was an important factor. According to other experiments he concluded that there was the same pressure exercised over the foot of the tube and that this pressure was constant[115]. He carried out a few experiments on the centrifugal force as well as on the oscillations of the triangular pendulum[116].

Many of the propositions of small pieces written during the 1660s and early 1670s were used in the Horologium Oscillatorium of 1673. In 1673 and 1674, Huygens was working on a general theory for the isochronism of vibrations. Again he used geometry to deduce most of these theories. He was an engineer pioneering the field of 'new mechanics' whereby drawings of instruments were accompanied by the necessary geometry and theory deduced after performing experimental trials with them. This makes him a forerunner in mechanical engineering because he tried to do this for every instrument he created.

In some short pieces of this time, Huygens compared the newly developed theory of harmonic vibrations to cycloidal oscillations. He then worked out their isochronism for different amplitudes. He stated that the inherent forces of bodies came from something different (weight/gravity, elasticity, etc.). He carried out experiments on these subjects too until he found the general theory of the isochronism of vibrations[117]. Motion was at the basis of his mechanics and also of his theories of light and matter.

4. THEORIES ON LIGHT. *DISCOURS DE LA CAUSE DE LA PESANTEUR.*, THE MAGNET.

During his trip of 1661, Huygens presented, in France, a refutation of Cartesian theories on light. Later on, in the 1690s he developed this theory further and, also, that on pesanteur influenced, mainly, by Greek atomists. He followed the Ancients' theories more closely than Gassendi. Huygens believed, like Gassendi that everything in the universe was made up of atoms. However, they differed fundamentally on basic aspects of their theories. Huygens did not refer to God as the creator of the atoms, which made up the whole universe, as Gassendi did. Furthermore, when Huygens described his theory of light, he also rejected the Cartesian whirlpools[118] and moved fully into an atomistic description of the particles, which propagated light. For Gassendi, light was also made up of atoms.

Gassendi translated Epicurus, Lucretius and other Ancients. Although he believed that the whole universe was made up of atoms[119], he found

Epicurus too unreligious because he did not attribute to God their creation. Gassendi found the theory of atoms handy to explain the way the universe worked, but did not accept Epicurus' statement that atoms were eternal and uncreated, nor that they had inherent impetus. Their mobility was simply given to them by God[120]. Huygens found Epicurus more convincing. Epicurus was more atomist than it had been assumed. He did not mention God as the original cause of the atoms in the universe, nor had he given them motion. To this Huygens added the concept of an infinity of atoms which could create a continuous number of matters, and subtle matter was one of them. He also added to this the indivisibility of atoms and the fact that they fluttered about, in all directions, as Lucretius had postulated[121]. Huygens' atomistic theory differed from both Gassendi and Descartes. The framework Huygens devised simplified his system of motion. The collision of hard bodies he transferred to atoms which formed the different matters. The laws of impact had been developed in 1656 as well as the first hypothesis on the transmission of light found[122] in one of its appendices. Light was transmitted from objects by the impact of one corpuscle on the next. The theory on the impact of hard bodies complemented the transmission of light perfectly. If two hard bodies of the same size and speed maintained the same speed after impact, it would also apply for corpuscles. He defined a continuous transmission, from corpuscle to corpuscle. I agree with Westfall in that the only action in a system of atoms is the impact of one atom on the next[123]. This I believe was the way Huygens saw it.

The transmission of light was fully clarified in his correspondence with Leibniz between 1692 and 1693. In the matter theory of 1692 the size of the atoms forming the various matters was infinite. One of these matters transmitted light and its atoms collided 'ad infinitum' until the observer perceived the object. Moreover, since the atoms were considered hard bodies, they collided preserving the same momentum after impact. In this system of infinitely small particles there could not be absorption of motion from one collision to the next because all the atoms were the same for each specific matter and of an infinitely small size. This theory proved that light was transmitted in waves like those seen on water after throwing a stone. Furthermore, from each centre of impact in each wave, more waves were formed and the impact remained unchanged from atom to atom, and from wave to wave. In 1693 Huygens referred to impact as preserved infinitely because he defined an infinite hardness (*duretè infini*). He said that this hypothesis was necessary and could not understand why Leibniz found it strange: "*l'hypothese de la duretè infinie me paroit donc trés necessaire et je ne conçois pourquoy vous la trouvez si estrange*"[124]. With the hypothesis of infinite hardness, impact could be transmitted 'ad infinitum'.

The treatise On Light (La Lumière) described studies in optics, reflection of light and, most importantly, the physical properties of light with a series of hypothesis based on Atomism. This treatise is made up of a series of models progressively improved[125]. Huygens said in the preface that he had written the treatise in 1678 in France and that he had communicated it to the learned men of the Academy. He worked on the incidence of light upon glass and on reflection and refraction, topics also studied by Newton and Leibniz. He used geometry to explain the different models of this treatise and observed the formation of Iceland crystal (*Cristal d'Islande*)[126] and rock crystal[127].

Huygens compared the propagation of light with that of sound, but his theories do not follow the logical demonstrations of previous treatises.

He was trying to explain an intuitive idea without a developed scientific method. Nevertheless, he followed a pattern. He referred to motion, the spirit of De Motu, and he tried to use geometry as he had done for the clock. Nevertheless, light did not work in the same way. He could not find an easy law to express his idea; he struggled with the methods he was familiar with. This treatise was not published before 1690 because he wanted to include also his work on Dioptrics, which was linked to telescopes[128] (see chapter 4).

With his own corpuscular philosophy he derived the physical properties of light and its motion in space. He believed that light was propagated in waves of particles that transmitted the light from one particle to the neighboring ones by direct contact. In optics he applied ellipses, hyperbola and other curved lines previously used for this purpose by Descartes. Huygens deduced the laws of reflection[129] and refraction following his geometrical method[130]. He believed that luminosity sprang from the bodies themselves and light consisted of the motion of the matter of light from the luminous object to the observer[131].

A comparison with the propagation of sound is very interesting. Sound was transmitted everywhere from one particle of air to the next. They kept expanding in a spherical manner until they hit the listener, in the same way as light expanded gradually on spherical waves and surfaces, like the ripples observed when a stone is thrown into water and from atom to atom[132]. Hooke also compared sound and light. He gave the example of a stick agitated in the air. If moved very quickly sound could be heard, but not so if moved slowly[133]. Descartes influenced him when he stated that the propagation of light was indefinite, whereas for

Huygens it was clearly infinite. Huygens was less Cartesian than even Hooke in some instances, contrary to what has been stated[134].

Huygens demonstrated that time was a factor in the propagation of light by observing eclipses of the moon and the motion of planets when they became visible in the sky[135]. It was important to take into account the ether, which surrounded the planets because the light had to pass through it. He concluded that light would move through these tiny particles of ether as follows: the motion of light was transmitted from one particle to the next with the same velocity following the established laws of impact. One particle would collide with the adjacent particle, and it would come into contact with the closest ones; these in turn would transmit the motion to those surrounding them. Light was in this way propagated in spherical waves and at great velocity, making astronomical observations possible. These waves traversed others as they were propagated from different parts of the luminous body, and so the observer was able to see the whole object and recognize it (figure 9).

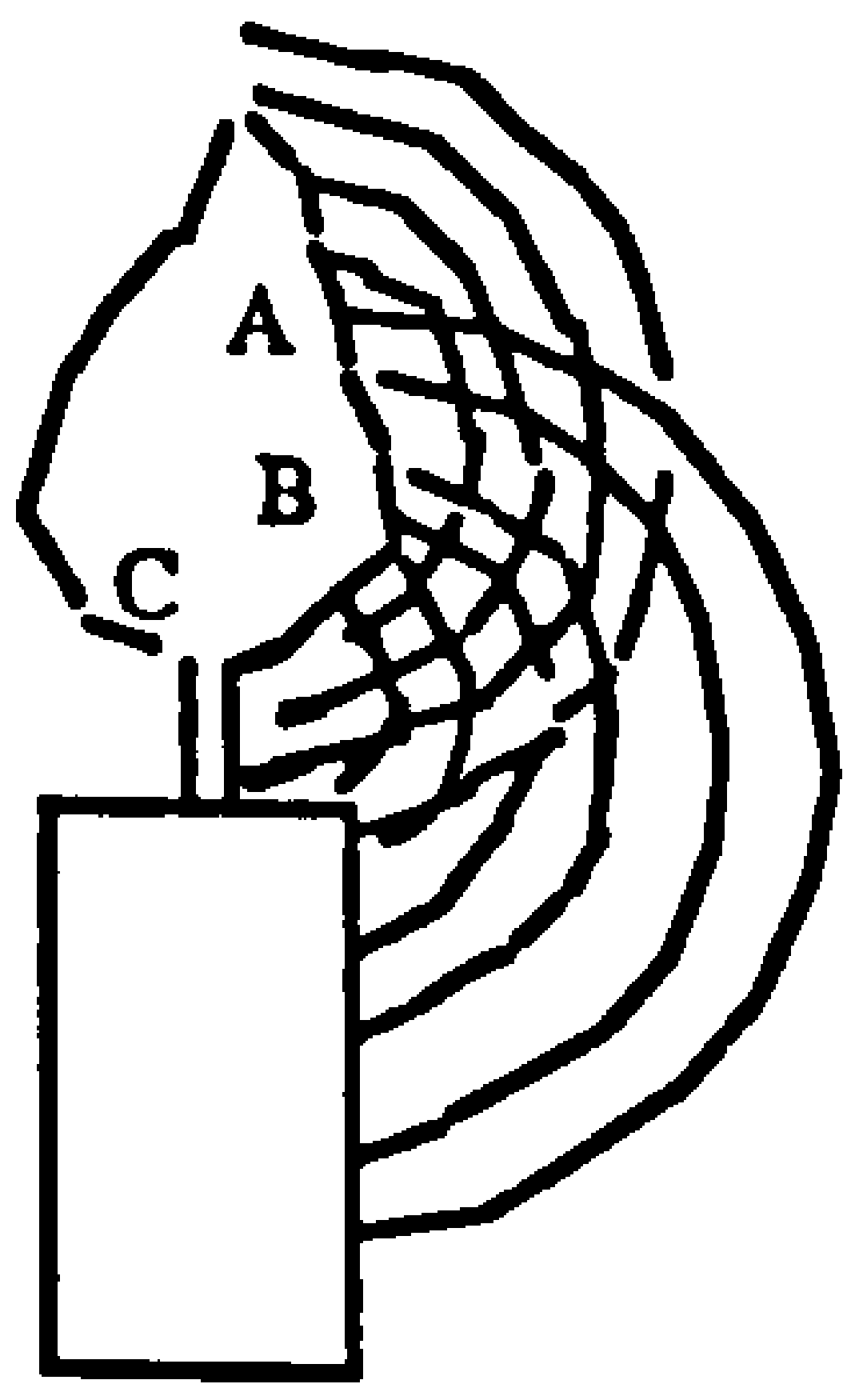

Figure 9. Propagation of light from a candle through spherical waves.

The waves expanded as they moved away from the object. There were several centres, each one with concentric circles that propagated light. These circles did not interfere with each other; the light was still transmitted from all the luminous centres, as shown in figure 9. Huygens was astonished by his conclusion: this system of tiny particles could cross immense distances to bring to earth images of the sun and stars[136].

In 1686-7, Huygens worked on the cause of weight/gravity and in the treatise: De la Cause de la pesanteur[137]. It was a continuation of some writing he had began on the subject in 1669[138]. The final piece was not published until 1693[139]. Already in 1668 Huygens had written about the cause of gravity. In a few pages on the De Gravitate, he pointed out the difference between him and Descartes on the cause of weight/gravity of bodies. Huygens first defined the cause of weight/gravity as the tendency that made bodies move towards the same centre. The two primary motions, rectilinear and circular supported his theory[140]. Later on, he introduced the concept of subtle matter, which could traverse all bodies, as the cause of pesanteur and compared it to the motion of wood in a round bowl full of water, but moving very quickly in many directions[141]. When its atoms bumped onto each other they followed a circular motion after impact because they were spherical in shape and were confined to a specific enclosure[142]. However, for Descartes pesanteur was the motion of a certain matter moving around the earth.

In Huygens' system a characteristic of bodies in circular motion was their tendency to flee the centre. The same force that made bodies flee the centre kept their tendency toward that centre forming spirals. The air and ether moved with the earth's daily motion. The matter surrounding the earth was fluid, made up of very small parts, moving very quickly in all directions, the majority of these motions were found on the spherical surface of the space which contained the earth[143]. It was this circular motion around the earth of the very tiny particles of fluid matter that caused the weight/gravity on its surface. All bodies on earth were carried with it in its motion. For instance, metals would have more fluid matter than other elements because they had bigger pores[144]. In the rest of the universe this fluid matter moved even quicker, and its particles could traverse any solid body as easily as they could traverse air. This was easily understood if compared to magnets. The magnet was observed to act the same in air as in the void[145], metals were still attracted to it. This free motion of the small particles was another property of fluid matter, and the weight/gravity of each body was in relation to the size of the particles, which formed it. Subtle matter passed through these particles and pushed the body towards the centre of the earth. The body, therefore, would have more or less pesanteur, according to how many small particles had to traverse it. The greater the quantity, the greater its weight/gravity was[146].

On 28 August 1669, Huygens defended these ideas before the Académie des Sciences against Roberval, Frenicle and Bout who had misunderstandood them. Huygens was convinced that motion of matter was the most intelligible explanation of weight/gravity[147]. On 7 August, Roberval had said that pesanteur was what made a body fall without artifice, by nature only. A week later, Frenicle agreed with Roberval and said that the magnet, which attracted iron at a distance without touching it, only caused attraction. Weight/gravity was nothing more than the action by which the parts of the earth were kept together. It was the action of magnetism that caused gravity. Although Bout did not believe in action at a distance, he agreed with Roberval in his criticism[148]. Later, in September, Roberval, together with Mariotte, commented on these ideas again. According to them Huygens had failed to explain forces of attraction between bodies. Forces were divided according to size, shapes and motion. Another important point in debate was the statement that all circular motions had the same centre. They also criticized Huygens' argument, on rectilinear and on circular motions used to explain pesanteur of objects on earth and in the universe. Finally, they thought that Huygens' fluid matter was, somehow, chaotic[149].

Huygens replied on October saying that he had not discussed forces of attraction and repulsion because he wanted to find an intelligible explanation for weight/gravity. At this point he was obviously still trying to find the right definition of a concept which he was developing with his own division of matter. Bodies fell on the surface of the earth because of their size (grandeur) and motion, and not because the earth attracted them. The relation between circular motion and rectilinear motion was necessary, because all bodies moving circularly had, when released, a tendency to move in a rectilinear motion towards the centre of the circle and tended to follow the tangent at the point where they had been released. The fluid matter, the cause of the pesanteur, moved in circular motion and in different directions too. Finally, he said that the fluid matter would not seem chaotic if it was understood as a fluid which could traverse solid bodies just as water in a river traversed reeds[150].

Huygens had the Discours de la Cause de la Pesanteur printed in 1690[151], but it was released three years later. He proposed an alternative theory to Newton's. Instead of ether he now thought of small particles filling everything and moving circularly around planets. He accepted Newton's theory as pesanteur acquired in the motion towards the sun, which was inversely proportional to the square of the distance, a theory that also explained Kepler's law of elliptical planetary orbits.

In the preface to the Discours, Huygens commented on the difficulty philosophers had had in the past to find the cause that made bodies fall onto the surface of the earth. He continued with the subject until the 1690s. It had been referred to as some internal or inherent quality to bodies, which made them fall or tend towards the centre of the earth. Huygens said that he had developed his own completely new theory on the subject, and that it was quite different from Descartes'[152], including his concept of fluid matter, as he sometimes referred to subtle matter. Maybe Huygens wanted to distinguish it from subtle matter. He refers to fluid matter as that surrounding the earth and the planets and any other system in the universe.

The first designed experiment on circular motion was that of a body tied to a cord and made to move in a circle. The hand that held the cord felt a tension, a pull from the body in question. In the Discours he added a second experiment. He tried a round table with a hole in the middle and a pivot or post traversed it. When he made the table turn, fluid matter was also turning and occupying the entire surface, describing concentric circles. All the particles of this fluid had the tendency to flee the centre as the table turned. However, if one particle did not follow this motion, it would come closer and closer to the centre[153].

Another experiment provided a better demonstration. It had been already described in 1668. A piece of wood, or Spanish wax, was placed in a cylinder with water, which in turn was put in the centre of the table. When a circular motion was induced in the water, the piece of wood remained at an outer circle within the cylinder. But when the table was suddenly stopped the piece of wood moved immediately to the centre of the cylinder. Huygens described this as the body's weight/gravity.

Furthermore, just as water carried the piece of wood in its circular motion, the earth also carried everything in its daily circular motion. Bodies were pushed towards the centre of the earth, in the same way as the piece of wood had moved towards the centre of the water in the cylinder. Pesanteur was the effort made by the fluid matter which turned around the centre of the earth, in all directions, to flee from the centre and to push in its place the bodies which did not follow its circular motion[154].

4.1. The magnet

Thomas Aquinas attributed to magnetism a supernatural action, whereas for Augustine it was caused by the action of demons[155]. Gilbert changed this tradition completely. Magnetism became a physical property of an object: the magnet. Huygens defined its properties with his theory of matter. This is one more example of the dramatic shift that the 'new science' was taking in the seventeenth century, away from the Aristotelian tradition.

Huygens began in the late 1660s to describe how he understood the way the magnet worked and drew several magnets and their respective magnetic forces. In his early work he recognized Gilbert as a pioneer on the subject who inspired him on this issue[156]. The magnetic matter moved in concentric circles at both sides of the magnet. These whirlpools attracted the matter nearby towards the iron of the magnet[157]. In 1678 Huygens believed that magnetic matter was thinner than ether, but not as fine as subtle matter. Otherwise magnetic matter would traverse all bodies too and they would all acquire the properties of the magnet. He compared the kind of whirlpools formed around the magnet to the motion of urine seen through the microscope[158].

The treatise on the magnet (Traité de l'aimant) was read in two sessions at the Academy: in May 1680 and in June[159]. That year he wrote several comprehensive pieces on the magnet. They showed that the motion of magnetic matter was different from that found in water and in air. The whirlpool formed by it moved like a liquid, very quickly, in straight lines within the magnet and in concentric circles outside it[160]. He drew these lines according to what he had seen in the experiments carried out (see figure 10). This matter flew constantly, in straight lines, within the magnet only to continue in semi-circles and to enter the magnet again through the other pole. This fluidity gave the magnet its physical property of attraction at a distance, so that any iron found in the vicinity of these circles would come close to it. Huygens did not believe that attraction at a distance was possible between planets and, therefore, he rejected Newton's theory of gravitation of 1687. For Huygens, attraction at a distance in nature only existed by the action of the magnet and was caused by the magnetic matter.

Furthermore, magnets could attract or 'repel' each other. The magnetic matter flew from one side of the magnet to the other, from the pole of entry to the pole of exit, in a continuous way. If the magnets were facing each other on their poles of exit, they reversed back to preserve their own concentric circles around the magnet, which produced repulsion. If, on the contrary, the magnets came together facing their respective poles of entry they came closer together because like with iron there was attraction (see figure 10).

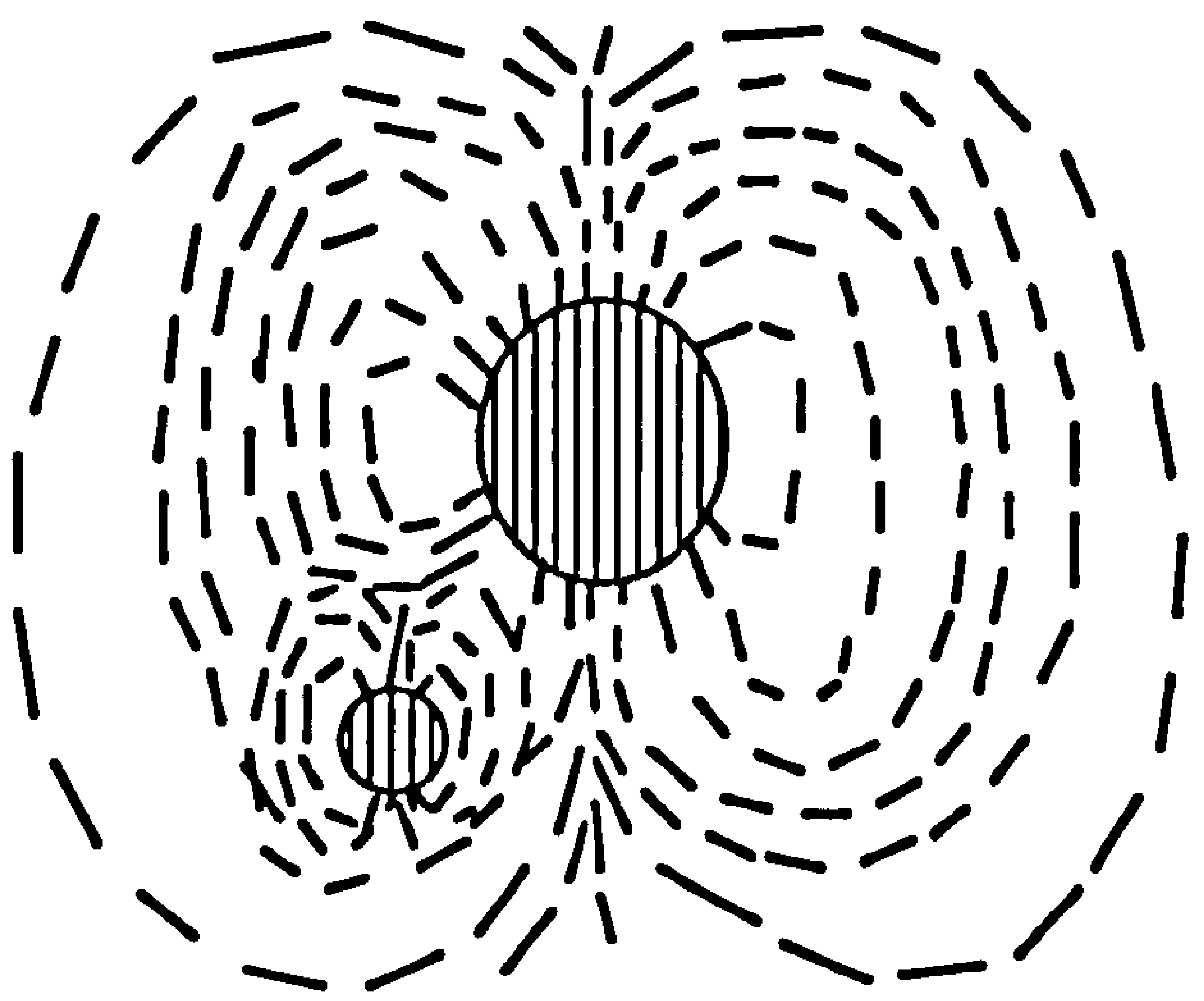

Figure 10 - Magnets of 1680[161].

By 1680, Huygens had defined the main matters found in nature divided according to the different sizes of particles. These were: ether, magnetic matter and subtle matter, each one made up of particles increasingly smaller. How did the magnetic matter compare to the other known matters so far defined, such as ether and subtle matter? Ethereal matter had to be bigger than magnetic matter because otherwise it would traverse the pores of the magnet, also, it had to be bigger than subtle matter. Neither could ethereal matter occupy the pores of the magnet. Furthermore, ether and subtle matter were important to describe the causes of experiments with the void, for the U tube[162] and the inverted tube.

Huygens' search for an explanation of the observed phenomena in the air-pump also took him into the realm of electricity. The Ancients knew the properties of attraction of rubbed amber; Gilbert and Von Guericke had referred to electric flow or electric bodies[163]. Huygens heard about Von Guericke for the first time in 1672, when Leibniz wrote to him suggesting a book by Gilbert to clarify his experiments of rubbed amber[164] and on the ball of glass filled with mercury. Huygens used different materials from Von Guericke who had used sulfur and other minerals melted in a glass ball, which attracted objects when, rubbed with the hands[165]. Von Guericke worked with sulfur as a new experiment following his work with the air-pump[166]. He wanted to demonstrate that the mixture of minerals with greater proportion of sulfur acted as a magnet attracting things to it. In the same manner, planets in the universe moved maintaining their orbits. Von Guericke was not aware of having produced static electricity, but rather that he had reproduced how the magnet and the earth attracted objects to their surface[167]. Huygens tried the experiment with amber but it did not work. The disappointment led him to abandon electricity until later, in 1692, when once again he experimented on the glass ball filled with melted mercury. The attraction of certain objects to the surface of the glass he called "electric vortices" (*tourbillons électriques*). In 1687, Huygens exchanged ideas on electric attraction with Von Tschirnhaus[168]. In this correspondence, and with Leibniz in 1690, Huygens realized that he had difficulties in explaining the electrical phenomena and found them more complicated than those of the magnet[169]. Leibniz said that he would write to Von Guericke who had carried out many experiments with electrical bodies (*corps electriques*) and asked his opinion about the problems Huygens was having with the amber[170]. Huygens used different objects: feathers, flakes of linen, cotton and very small plants. Unlike Von Guericke, he realized that this was a different physical phenomenon from the magnet. These new phenomena did not seem to fit with the theory of matter he had deduced. He talked of electric whirlpools, maybe as a reference to the magnet, but said nothing of an electric matter. Neither did the attraction of objects to the rubbed glass follow a theory of atoms. On the contrary, if anything it seemed to disrupt it. Huygens gave up these studies because the new phenomena could not be defined with the theories he had evolved. Electricity was further developed in the eighteenth century[171].

He needed to develop a physical theory to explain motion, pesanteur and the different matters, which gave their properties to the natural elements. The matters he distinguished clearly were ether and subtle matter, as well as magnetic matter, but there were other phenomena, for instance electricity, which he could only define as electric matter, and which was not developed any further. This shows the limitations of the physical theories available. Electricity baffled scientists for many years to come.

4.2. The form of the earth, weight and 'gravity'.

Of all the matters Huygens referred to, subtle/fluid was the most important one. Most of his physics consisted of his attempts to define matter. It is not surprising to find a constant reference to this, from the first experiments with the air-pump, right to the early 1690s. The size of subtle matter particles was between those found in the air and those of a fluid. They had to be smaller than air, because they could traverse the tube used in the receiver of the air-pump. They were bigger than the fluid matter, which caused the pesanteur, nor did it follow its motion[172]. Later on, Huygens defined weight, as the amount of matter a body was made of[173].

Huygens discussed the speed at which the fluid matter moved around the earth by comparing the circular motion of its particles with that of a good working pendulum. He expressed his concern about how different climates could affect the clock and, consequently, the measure of longitude. He referred to this measure, the use of his method to find it, and to how to calculate the different lengths of the pendulums at different latitudes[174].

The form of the earth had an influence on the pesanteur of bodies. Huygens accepted the centripetal force that, according to Newton, caused the planets to tend towards the sun and the moon towards the earth following elliptical orbits[175]. Another important Newtonian concept which Huygens accepted was matter as defined in Proposition 6 of Book III of the Principia, but he did not accept gravity. In the 1690s, Huygens defined weight/gravity as the amount of matter the bodies contained. He also agreed with the law of attraction of satellites to their planets, which was in inverse ratio to the square of the distances from the centres of their orbits[176].

The matter that caused the pesanteur passed freely through the most solid of bodies with the same ease as it traversed air[177]. It existed in an infinitely diluted form, compared to that of water, in the celestial matter. It circled around the centre of the Earth in all directions and tended to expand and occupy the place of bodies that do not follow this movement[178]. For Huygens this matter was formed of infinitely small atoms, smaller than air and it acted as a fluid. It was easier for a liquid moving circularly to create a whirlpool where any objects would tend towards its centre. This matter maintained the body's shape because all its molecules tended towards their centre of "pesanteur", in the same way that planets were kept circling in the universe.

In 1692, in a letter to Leibniz, Huygens expressed how difficult he found understanding Newton's definition of gravity as attraction at a distance.

However, Huygens did support the idea of the existence of ether engulfing the planets that held them in their elliptical orbits. The new laws of physics were being defined in an attempt to explain the phenomena observed in the universe and to replace a very different tradition: from a philosophically-based system to one supported by observations (astronomy, air-pump, microscope) and defined by the theories developed from experimentation. These laws were finding an increasing support within natural science during the seventeenth century. It was realized that the old tradition was insufficient to explain the phenomena observed with the new instruments.

Huygens analyzed different motions of bodies on air by following the rule that the bodies were in ratio between them as the speeds acquired by their forces of resistance. In the case of falling bodies he drew geometrical diagrams and found the appropriate ratios for that resistance. He combined vertical and horizontal motions, and determined the ratio between them[179]. Motion and space became important issues and discussed them throughout his works in the late 1680s, especially relativity of motion.

5. ABSOLUTE SPACE AND RELATIVE MOTION

Relative motion stood at the core of Huygens' work on rectilinear and circular motions. It showed his radical breaking away from Descartes whose theories were not compatible with his concept of relativity. Joannes de Raey developed a very polemical attack against Descartes at Leyden University in 1652. Raey did not try to find experiments to disprove Cartesian theories of motion, but relied on a philosophical argument. He disagreed with Descartes' doctrines because they were incompatible, not only with themselves, but also with relative motion, the laws of impact, and total motion in the world[180].

Huygens did not study motion with respect to space before 1687. In 1669, he had written that motion and rest could be considered as relative. A body could move with regard to other bodies, or be equally at rest[181] The motion of a body could be at one moment equally at rest or accelerated[182] and in relative motion due to either uniform or to accelerated motion. They were explained in De Vis Centrifuga of 1658. The wheel turning represented the uniform and accelerated motions with an observer attached to the wheel. Due to the relative-accelerated motion, the small body exercised a force/traction over the hand that held it[183].

Later, in 1675 and in 1676, Huygens worked on the principle of motion of a body under the influence of an external material agent or of an unknown cause. When a body moved, for Huygens, it followed a straight line unless something diminished such motion progressively, or impelled motion upon it again, accelerating it. The force that acted in this way Huygens called *incitation*. (See chapter 1).

Huygens was not convinced about Newton's conclusions on absolute space and he questioned its existence. He seems to have accepted absolute motion[184], but not absolute space[185]. In 1688, he wrote that the directions of any motion were not absolute, but the changes of directions in a void had an absolute character[186]. However, Newton influenced him towards the end of his life when he referred to gravity[187] and not pesanteur. But it still meant weight rather than attraction at a distance.

Huygens was not only interested in getting to know the basic laws of how nature worked. He had a deep interest in cosmology. He wanted to know more about the universe and find the laws that governed it. He read and commented on the cosmologies of Bruno[188], Kepler, and others. Bruno in the 16th century had been burnt at the stake for, amongst other accusations, daring to make the earth mobile, which was considered heresy. His cosmology had removed the Aristotelian sphere of fixed stars and opened an infinite universe to man.

Huygens also believed in an infinite universe. The studies on systems of the universe made him define his own ideas about relative and absolute motion, and even to describe a whole cosmology. This might have been a direct influence of the meetings held at Fontenelle's where they discussed the possibility of life in the universe. It must have inspired Huygens to write his cosmology, which he saw as a culmination of his work on motion and matter.

6. HUYGENS' COSMOLOGY

For Huygens, the existence of similar beings in other universes was deducible from the perceived similarities in the astronomical observations of the planets. The different kinds of matter would also have to exist in them and have the same properties as in the solar system. He extended to the whole of the universe all the physical properties of his theory of matter. Ether would fill space, magnetic matter would preserve its property of attraction at a distance and subtle matter would be the cause of <u>pesanteur</u> in those universes too.

In 1690, Huygens wrote a small treatise, the Cosmetheoros, about the existence of other living beings in those planets[189]. Here he asserted that there was a high probability of life on other planets. He developed an idea of progression -I would say, as a kind of evolution- as he described each planet of the solar system. Huygens suggested that perhaps the humans and other living beings found in them were superior to us in some way, because he thought they had developed on the other planets before us[190]. His admiration for what he observed in the skies was reflected in his description of beings living on other planets as maybe superior to us. For instance, he believed that the Martians were more advanced and beautiful than people on Earth since Mars appeared as such a beautiful planet through the telescope[191]. He was convinced that all the observations of the different planets he had carried out proved the existence of planets similar to earth and, therefore, that they must have similar life on them.

The treatise of the Cosmetheoros may have been written in 1694 because he wrote to Constantijn about it[192]. Huygens wrote this treatise to clarify how the universe might be designed. Some appendices to it are also of that year[193], but the exact date when Huygens started to write it, is unknown. Constantijn, to whom it had been dedicated[194], published it posthumously, in 1698[195]. Huygens found a lack in the history of cosmology because nobody had so far attempted to explain the whole of the universe with all its planets and distant stars. The Ancients had failed to do this[196], similarly Bruno, Kepler, and Tycho Brahe.

Against possible criticism from those Huygens called "*less instructed* ", who might believe his treatise vain or ridiculous, he said that they would not understand the aim of the treatise unless they had the basic knowledge of geometry or mathematics required to do so. He also defended himself from possible religious attacks, by stating that his work was not against the Scriptures, because it did not say who had created what. It simply described what he thought was there in the universe. It was solely based on the astronomical observations that he and others had carried out[197].

Huygens declared that there were other worlds in the universe, but he could only speculate about whom their inhabitants were[198]. He described the solar system, the stars, the dimensions of planets[199], and the way to calculate the distances of the stars to the sun[200]. In this huge system, the earth was but a small particle[201]. He believed there were a multitude of worlds similar to ours[202]. The first planets he compared the earth with were those of the solar system because he had observed them with his telescope more and concluded that they must contain similar life because their physical characteristics resembled those seen on earth. They were spherical, and all received light from the sun. Furthermore, they all revolved around their own axis, and some of them such as Saturn and Jupiter, also had moons[203]. In the same way that atoms made up the natural elements and the whole universe, it was only logical to think that these atoms would also form the same elements in other planets[204]. Moreover, the Creator might have, at the beginning, also created living beings on those planets, which might be more or less similar to ours[205] and, therefore, with a similar atmosphere.

The inhabitants of all the planets in the universe, Huygens called *planéticoles*[206]. They might also be studying the universe and be interested in astronomy and all other sciences, as we are[207]. Their appearance might be similar to that of humans on earth, they could be living in society and be familiar with music, geometry and other fields of knowledge. Therefore, there also had to be astronomers and musicians[208].

He doubted that the moon would have living beings because he thought it had no atmosphere[209]. The other suns, which might form other solar systems, were set in motion by whirlpools that, as Huygens explained, were very different from those described by Descartes. The planets were kept in motion within the whirlpools, which in turn touched each other maintaining a constant motion. Huygens' whirlpools were directly connected to gravity. Influenced by Newton who, Huygens said, had explained it with great clarity and diligence[210], he stated that the planets were surrounded by an ether which made them circle around the sun in a manner similar to Newton's rings. However, Huygens' *tourbillons* (but described as waves) could be compared to those observed in a pond when a stone is thrown, creating increasingly bigger circles but, in the case of the planets, following ellipses[211]. The planets stayed in their orbits because of the gravity, which pulled them towards the sun. He defined gravity in the whole universe, applying his concept of ether to the other stars and universes because he thought they were similar to ours.

Science fiction could have begun with 17th century theories on other planets. In the second part of this treatise, Huygens said that it would be possible to know if what he had deduced was true, by flying around the universe. If genies existed –this must have been influenced by Arab story-telling- Huygens with Kircher agreed that they could fly the universe and bring news of the existence of other worlds. Kircher had mentioned the "genie astronomique"[212] and Huygens referred to it in his Cosmetheoros[213].

7. CONCLUSION

The studies on rectilinear and circular motions were at the basis of his main theories, from isochronism, to centrifugal force, speed of air, or transmission of light, but above all in every work on mechanics. Nevertheless, natural elements were made up of infinitely small particles of different sizes. He had to develop a theory that would explain the physical properties of these particles in relation to the space they occupied. His studies on the relativity of uniform and circular motions helped him to develop a theory of matter, which described the physical properties of particles with respect to others in space and in the universe. He retained some Cartesian influence because he believed in the existence of a passive, inert matter. Motion was, therefore, essential for the full development of Huygens' mechanics.

In Huygens' theory of matter two important postulates should be taken into account. First, atoms in the universe moved in all directions. Second, a specific source of impact was transmitted 'ad infinitum' from atom to atom, e.g. in the case of transmission of light: from the object until it reached the observer. Huygens differed from Descartes and Gassendi on both postulates, and from both Ancient atomists and contemporaries on the second. Subtle matter was made up of tiny particles. It was different from anything corporeal known since, unlike air, it could not be sensed, or experimented upon. Therefore, Huygens could not be called a plenist.

Huygens' matter theory was obviously different from that of his contemporaries. It was more atomist than Cartesian. Furthermore, he followed the atomism of the Ancients without a metaphysical influence from the Aristotelian tradition. He did not need causal theology but atoms as primary causes. The origins of the universe showed God's hand, but its working was merely based on the explanation of physical properties and basic laws. Huygens was more atomist than Gassendi. Snelders states that Huygens had accepted Cartesian physics, only modified with Gassendi's theories[214]. Huygens went even further. Apart from atoms, void also existed in the universe. Unlike Epicurus and Lucretius, who defined atom as being and void as not being (Gassendi, 1972), Huygens seemed to believe in void as void of air. Therefore, it was, it existed as an "emptiness" of air, but not of subtle matter which could not be emptied from the vacuum formed in the air-pump. Helden (1991) does not make this distinction. Huygens was not a plenist in the sense this concept was understood in the seventeenth century. The introduction of the concept of subtle matter was twofold: on the one hand, it created a physical theory for the phenomena observed in the void, on the other hand, it was easy to explain these and the universe with matters of an infinite number of atoms of smaller size. Therefore, why did he not define a new matter, electrical matter, to explain the electric whirlpools he believed caused the attraction to the rubbed amber? The reason was simple; he did not understand the phenomenon. Would it be formed of parallel and concentric circles like the magnet? Huygens did not define this phenomenon because the experiments were unsuccessful. It would be right to think that he would have used the concept of a matter formed of small particles to define it. Although he left it like that, he perceived the difference between the attraction exercised by the magnet and that seen by rubbed amber, whereas Von Guericke did not. It could be argued that Huygens got the experiment wrong because he used mercury instead of sulfur. However, the experiments were performed over several years. He had time to read about Von Guericke and reproduce the experiment. Instead, he continued using mercury. In my opinion, this was one more proof of the experimenter trying different materials to see what they would do, rather than reproducing the materials found on earth, which was Von Guericke's aim.

Huygens did not use arithmetic notation to define the various matters physically, but he realized the fundamental differences between them. Magnetic matter acted in concentric circles and lines around the magnet and through it, creating a field of action around it. Weight/gravity was the fluid matter, which filled all the space and traversed bodies. It was more a concept of mass/weight than of mass/gravity. This concept Newton changed and defined as attraction of bodies at a distance. Over the years, these concepts were integrated in dynamics as: magnetic field and force of attraction with corresponding formulae.

Huygens could not understand Newton's gravity because he did not believe in action at a distance. However, Huygens' theory of matter was more influenced by the atomism of Democritus and Gassendi than by Descartes. He believed in different sizes of particles, atoms, making up different kinds of matter such as: ether, magnetic matter and, finally, subtle matter. Ether surrounded the planets not as inert vortices, as Descartes had described, but as dynamic particles impacting against each other, moving with different motions. Magnetic matter was the only way by which objects could be attracted at a distance. He did not believe this could be the case with planets too. Fluid/subtle matter could traverse all objects and was the cause of their pesanteur.

Huygens used the idea of whirlpools, but they were different from the Cartesian ones, as he kept repeating in all his works on gravity. This contradicts Snelders' claim (1989) that Huygens believed in the cause of gravity as a consequence of Cartesian whirlpools. Huygens' whirlpools were different; the particles were similar to atoms and moved in a random manner. I believe that Huygens used that term because the concept of 'chaos' had not yet entered the world of physics. Huygens' idea of weight/gravity was one in which others did not limit the whirlpools. And, although he did not believe in Newton's attraction between bodies at a distance, he agreed with the Newtonian centripetal force. By 1692, Huygens had no doubts about the pesanteur of planets being in inverse square of their distance to the sun and following ellipses, as Kepler had stated[215].

He was not modern in the sense it is understood today, but in the way science was understood then. Furthermore, Huygens pioneered a new way to study nature without the philosophical foundations that had characterized it so far. He broke with the then traditional philosophy and developed a new way by using some of the then modern physics available: Cartesian theories; the classic translations of Epicurus and Lucretius in Gassendi's works; Democritus, and his own theories. His mechanics were an important new step towards what we now call mechanics for engineering, and his statics and dynamics were a turning away from metaphysics. He had broken with the traditional way of explaining the laws of nature.

Some historians tend to look for concepts of physics in the way they are understood today. They seem to have a preconception about science in the past. However, I believe that the analysis of historical scientific texts should be carried out without reading modern science in the past. Modern notation should not become a way to differentiate between traditional, early modern and more modern ideas. The mechanics of the seventeenth century had a traditional base: Aristotelian physics. What was modern then was Cartesian philosophy, which described motion in a philosophical way. However, it influenced science, which developed very quickly, almost making Cartesianism obsolete before it had hardly been applied.

Huygens' theoretical physics showed his skills as a natural scientist rather than a natural philosopher as Hooke was. Huygens did not resort to philosophical discourse but to mechanics 'per se', developing empirical science further. Huygens' philosophical twist was cleverly designed to leave behind the old tradition of philosophical presentation.

On the whole, Huygens did not explain the mysteries of the universe any more than we are able to do so nowadays. The matter that surrounds the spirals of galaxies is still unknown today. A recent term for it is "dark matter" which seems to slow down the rotation of outer planets in a solar system. There is also the possibility that the neutrinos might be making up this dark matter which in turn seems to be holding the universe together. Or, maybe another particle exists, still to be discovered, which could be forming the dark matter. At the moment it is only known as an 'undetected-in-the-laboratory' kind of particle[216]. Ether does not come into anybody's mind these days, and even less the concept of subtle matter, but how wrong was a natural scientist of the seventeenth century in assuming that some type of matter with very small particles was holding the universe together? Recent work in astronomy has shown that after all the dark matter is 'ordinary matter'[217], only made of smaller particles. Does it sound familiar?

Huygens preferred to work with mechanics and machines, which he could design and explain with his geometrical mechanics. The next chapter will give a summary of other instruments that, although not as important as the clock, they show further his inventive skills and his pioneering work in mechanical engineering.

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[1] (Vol.1, p.303).

[2] (Vol. 19, p.164).

[3] (Westfall R., Force in Newton's Physics, 1971, p.58 and Descartes Principia, Pars III, 1644)

[4] (Vol.21, pp.507-8).

[5] (Vol.10, pp.403-5).

[6] (there is no exact date but he wrote to Pascal 20th July 1656 saying that he had written a complete treatise against Descartes laws of impact, treating him so badly. Vol.1, p.457).

[7] (Vol.1, p.301).

[8] (Vol.1, p.303).

[9] ("Caeterum cum novam Cartesij Geometriae editionem. Vol.1, letter 306, note 3).

[10] (1652-54, Vol.16, pp.92-4).

[11] (Vol.16, pp.94-7, 98).

[12] (Westfall, The construction of modern science, 1977, p.128).

[13] (Vol.16, pp.108-10, 122).

[14] (I. "Un corps quelconque, une fois en mouvement, si rien ne s'oppose, continue de se mouvoir avec perpétuellement la même vitesse et selon une ligne droite. II. Quelle que soit la cause que les corps durs rejaillissent de leur contact mutuel, quand ils ont poussés réciproquement l'un contre l'autre, nous supposons que deux corps durs, égaux entre eux, de même vitesse, lorsqu'ils se recontrent directement, rejaillissent chacun avec la même vitesse avec laquelle il était venu. III. Le mouvement des corps, et les vitesses égales, ou inégales, doivent être entendus respectivement comme ayant égard à leur relation avec d'autres corps qui son supposés comme étant en repos, quoique, peut-être, ceux-çi comme ceux-là soient sujets à quelque autre mouvement qui leur est commun. Par conséquent, lorsque deux corps se rencontrent, quoique les deux ensemble éprouvent quelque autre mouvement égal, ils n'agiront pas autrement l'un sur l'autre par rapport à celui qui est entraîné par le même mouvement commun, que comme si ce mouvement accessoire fut absent dans tous". Vol.16, pp.179-181).

[15] (Hypotheses I and II, Vol.16, pp.30-1).

[16] (Vol.16, pp.32-3).

[17] (Hypothesis IV, Vol.16 p.38-9. Vol.17, p. 271-2. Hypothesis V, Vol.16. pp.40-1).

[18] (January 1652 to Gutschoven, Vol. 1, p.167. In October to Schooten, Vol.1, p.186. In July Schooten had tried to fill the gap left by Descartes in the fourth law of impact, Vol.1, p.187-8. But Huygens wrote a very intelligent reply: November, Vol.1, p.457).

[19] (Gabbey, A. in Boss edit.1980, pp.166-199).

[20] (Descartes, Principia, 1644, Pars III, Adam & Tannery edit).

[21] (Editor's note 3: 1/2V'a-(1/2V'a-Vb)= Vb; Prop.IV, Vol.16, pp.42-3).

[22] (Prop.IX, Vol.16, pp.64-71).

[23] (Prop.XIII, Vol.16, pp.86-91).

[24] (Prop.V.Vol.16, pp.46-9).

[25] (Prop.VI, Vol.16, pp.48-51).

[26] (Prop.VII, Vol.16, pp.50-3).

[27] (Prop.XI, Vol.16, pp.72-7. Prop.XII, pp.80-7).

[28] (Prop.VIII, Vol.16, pp.52-65).

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[29] (Prop.V, Vol.16, pp.46-9).

[30] (Vol.16, pp.117-8).

[31] (Vol.16, pp.132-4).

[32] (Vol.16, pp.150-168).

[33] (Vol.1, p.186).

[34] (Vol.1, p.260, 307).

[35] (Vol.1, p.446).

[36] (Vol.2, p.79, 87, 94).

[37] (Vol.2, p.103).

[38] (Vol.1, p.115).

[39] (Hypothesis IV, Vol.16 p.38-9 and Prop.V, pp. 40-1).

[40] (Vol.2, p.123).

[41] (Vol.17, pp. 282-3).

[42] (" Ad metienda tempora gravium cadentium. Plumbum D et penduli pondus K simul dimittuntur, fecto funiculo quo ambo colligata tenentur. D laxum foramen habet, ita ut secundum funiculum BC libere decidere possit. cum vero descendit ad exiguum plumbum C, attrahit funiculum BC deorsum atque una chartaceam fasciolam BA funiculo cohaerentem. Quo fit ut motus penduli K tunc sistatur. notante stylo SO, qui pendulo infixus est, et fuligine infectus, quod punctum eo momento transeat chartae BA. puta R. unde addito spatio BR ad altitudinem DC, habetur altitudo tota quam certo numero oscillationum integrarum cum dimidia plumbum D deorsum confecit. Signatur autem charta AB vel anteriori parte vel postica, nam pendulum ita suspendum est ut cum quiescit stylus 0 fit sub charta ad perpendiculum" Vol.17, p.284).

[43] (Vol.6, pp. 276-7).

[44] (Birch Thomas, History of the Royal Society of London,1705-1766, printed in facsimile New York & London 1968 Vol.II, 1756, pp.116-7).

[45] (Birch, 1968, Vol.II, p.328).

[46] (Birch, 1968, Vol.II, p.335).

[47] (Birch, 1968, Vol.II, p.337. Huygens apologized about the delay.Vol.6, p.312).

[48] (To Oldenburg: "cette petite injustice" Vol.6, p.390. To Moray Vol.6, p.395. To Duhamel Vol.6, p.392).

[49] (Vol.6, p.356, 414-6, Duhamel 417, 422; 423-4; 427, 429-433).

[50] (Vol.6, p.439).

[51] (Vol.16, pp.179-182. Article, pp.182-6).

[52] (Vol.16, p.185).

[53] (Vol.16, pp.185-6).

[54] (Vol.17, pp.276-7).

[55] ("la gravité est la tendance à choir: si l'on admet qu'en vertu de cette tendance les corps pondérables qui tombent soit verticalement soit en suivant des plans inclinés se meuvent avec une accélération telle qu'en des temps égaux d'égales vitesses viennent s'ajouter à la vitesse acquise, on peut en se basant là-dessus démontrer rigouresement que les espaces parcourus en des temps différents par des corps partant du repos sont entre eux comme les carrés des temps. Or, ce résultat est en parfait accord avec l'expérience", Vol.16, pp.254-5).

[56] (Vol.16, pp. 254-5).

[57] (Vol.16, pp. 256-7, 258-267).

[58] (Vol.16, pp. 264-5).

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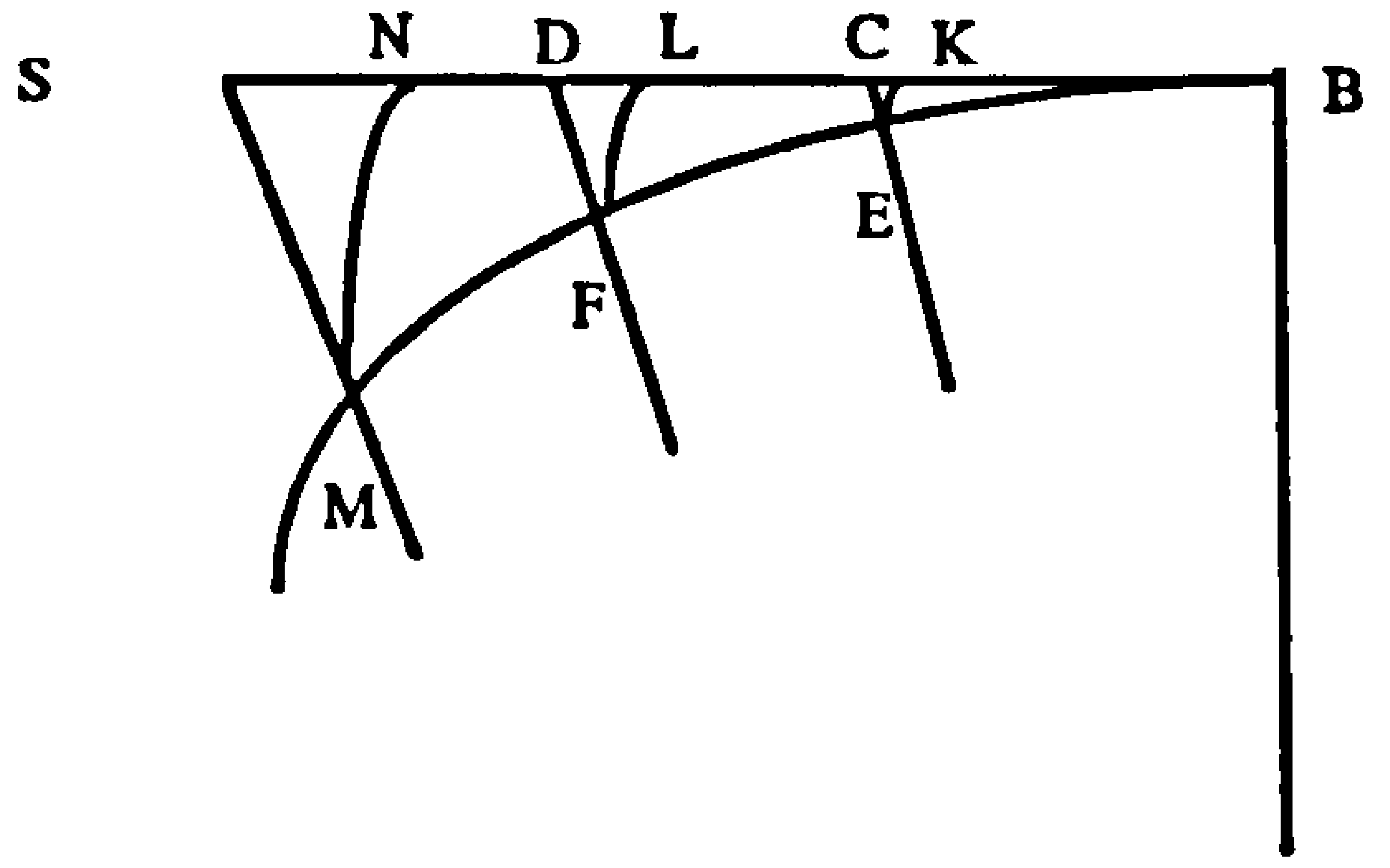
[59] (Figure 2 - The way centrifugal force works in circular motion:



The arcs BE, EF, FM are equal arcs of the circumference and BK, KL, LN are straight lines situated in the tangent to this circumference and equal to these arcs. The lines EC, FD and MS are linked to the centre. If the body was detached from the cord, which at the same time is turning, at B, for the first counted time the body would be at K while the point B would be at E. For the second counted time, while B reached F, the body would reach L, covering the arch FL. For the third period of time, while B reached M, the body would reach N and will have covered the arch MN. Because the arcs are very small they can be considered equal to lines EC, DF and SM. The force exercised by the body attached to the turning wheel will be that which would tend to follow the straight line, which links the body to the centre. It will have an accelerated motion by which it can cover in equal times distances following the numbers: 1, 3, 5, 7, etc. Vol.16, pp.264-7).

[60] (Prop.I-IV, Vol.16, pp.266-277).

[61] (Prop.XVI-XVII, Vol.16, pp.294-301).

[62] (Prop.IX-XV, Vol.16, pp.286-295).

[63] (25th of February or 21st July, Vol.16, p.327).

[64] (December 1667, Vol.6, p.164).

[65] (Vol.16, pp. 323-6).

[66] (Vol.18, p.636).

[67] (Vol.18, p.658).

[68] (Vol.10, p.703. On Absolute motion Vol.16, pp.213-233. On relative motion, Vol.16, p.198 note 5, 215, 232).

[69] (Vol.16, pp.201-12).

[70] (Vol.16, pp.201-4).

[71] (Vol.16 pp.213-233, 221-3).

[72] (Vol.10, pp.302-3).

[73] (Vol.15, p.459).

[74] (Vol.10, pp.645-6, 681).

[75] (Vol.10, pp.669-670).

[76] (As it has been explained in the introduction, Pesanteur was the term used by Huygens to mean weight/gravity).

[77] (Descartes, Principia, Vol.VIII, Pars Quarta, 1644, printed by Charles Adam & Paul Tannery, Paris, J. Vrin, 1973).

[78] (Gassendi died in September or October, dates vary because Huygens wrote to his father on September 24th and the Editor's date is 24th of October. Vol.1, p.342)

[79] (Vol.1, p.351, Gassendi died at Montmor's house where he lived the last two years of his life, p.399).

[80] ("Vous avez perdu un grand admirateur en seu M. Gassendi, qui faisoit desja grand cas de vous et qui est esté rauy s'il est veu le progres de vos descouvertes", Vol.1, p.483).

[81] (1656, Vol.1, pp.402-3).

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[82] (Letter from Chapelain, Vol.2, p.496).

[83] (Charleton, Walter, Physiologia Epicuro-Gassendo-Charletoniana, 1654; Epicurus' morals, 1656).

[84] (Birch, The History of the Royal Society of London, 1968, Vol.II, p.124).

[85] (1662, Vol.4, p.221).

[86] (Gassendi was Philosopher at Aix, also Professor of Mathematics at the *College de France*. After some time off he came back to Paris in 1653. Born in 1592, Gassendi died in October 1655. P.Gassendi, The Selected works of P. Gassendi, New York, 1972).

[87] (Kargon R.H., Atomism in England from Hariot to Newton, Oxford U P, 1966, p.67. P.Gassendi, The Selected works of P. Gassendi, New York, 1972).

[88] (Lloyd G.E.R., Early Greek Science: Thales to Aristotle, Chatto & Windus, London 1982, pp.45-7).

[89] (Shapin & Schaffer, Leviathan and the Air-pump, 1985, p.119).

[90] (Shapin & Schaffer, 1985, p.68).

[91] (Shapin & Schaffer, 1985, p.83).

[92] (Kargon, 1966, p.97, 100).

[93] (Vol.16, p.185, 210, 221).

[94] (Descartes, Principia, Vol.III, Pars III, (1644) 1973).

[95] (Vol.16, pp.379-383).

[96] (Vol.16, pp.384-5, 392-413).

[97] (Vol.16, p.385, 393-555).

[98] (Vol.16, p.475, 478).

[99] (Vol.4, p.194).

[100] (as the value of g was known by 17th century natural scientists. In modern terms it would be known as a universal constant).

[101] (Vol.19, pp. 23-6).

[102] ("adeo ut potentiae manubrium KL circumagentis vis trecenties jam multiplicata fit". Vol.19, pp.30-1).

[103] (Vol.19, pp. 32-47).

[104] (Vol.19, pp. 48-75).

[105] (Vol.19, p.102).

[106] (Vol.19, pp.106-119).

[107] (Vol.19, pp.120-7 "les vitesses d'un mesme corps sont en raison sous doublée des poids qui le tirent par l'eau" and later, "La force du poids est justement egale a la resistance de l'eau qu'il doibt traverser: et que par consequent ces puissances se contrebalanceroient de mesme" p.125).

[108] (Machines et Inventions approuvées par l'Académie Royale des Sciences depuis son établissement jusqu'à présent; avec leur description. Dessinées et publiées du consentement de l'Académie, par M. Gallon, Pièce V, Tome I, Paris, G. Martin. 1735).

[109] (Wednesday, 10th of April, 1669 and 15th May: pp.129-136, 29th May, pp.136-7; Vol.19, pp.128-137).

[110] (Vol.19, pp.132-3).

[111] (Vol.19, p.137).

[112] (Vol.19, pp.138-9).

[113] (Another way of measuring the speed of air was by observing the speed a body would acquire when falling on the ground due to the air. He designed one more instrument for this purpose. It consisted of a long post with a weight at the top and over a foot which was a metallic frame but the pole was mobile so that it could fall on the ground, Vol.19, pp.140-3.)

[114] (vol.19, pp.144-157).

[115] (Vol.19, pp.158- 173).

[116] (Vol.19, pp.174-180).

[117] (Vol.18, pp.489-495).

[118] (Descartes, Principia, Pars III, LXXVII).

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[119] (Gassendi P. Opera Omnia, "De vita et moribus, EPICURUS". Stuttgart-Bad Cannastatt, 1964, p.175).

[120] (Gassendi, Pierre, The Selected Works of P.Gassendi, translated by Craig B. Bush. Johnson Reprint Corporation, N.Y. 1972, pp.398-400).

[121] (Gassendi, 1972, p.422).

[122] (Hypothesis II. De Motu, Vol.16, pp.30-1).

[123] (R.Westfall, Force in Newton's Physics, New York 197, p.146).

[124] (Vol.10, pp.385-6).

[125] (Burch, Ch.B. Huygens' pulse models as a bridge between phenomena and Huygens' mechanical foundations, Janus, LXVIII, 1981, pp.53-64).

[126] (Vol.19, pp.494-5, 518-521, 544-8).

[127] (Vol.19, p.495).

[128] (Vol.19, pp.453-60).

[129] (Vol.19, pp.477-490).

[130] (Vol.19, pp.490-4, 498-518).

[131] (Vol.19, p.491).

[132] (Vol.19, pp.462-3).

[133] (This was due to the "parts of the air" moved in front of the stick quicker and they had been impressed of a certain motion they also move backwards around the stick and these parts moved swiftly around the stick. HOOKE, R. The Posthumous works of Robert Hooke. The sources of science, N.73. Johnson Reprint. N.Y. & London, 1969, p.116).

[134] (Hooke, Posthumous works, 1969, pp.76-7).

[135] (Vol.19, pp.462-471).

[136] (Vol.19, pp.472-7).

[137] (Vol.21, pp.379-382).

[138] (Vol.19, pp.631-640).

[139] (Vol.21, pp. 445-499).

[140] (Vol.19, p.631).

[141] (Vol.19, p.626-7).

[142] ("la raison de ce mouvement circulair est que la matiere contenue dans quelque espace, se meut plus aisement de cette matiere que par des mouvemens droits contraires les uns aux autres, lesquels mesme en se reflechissant, (parce que la matiere ne peut pas sortir de l'espace qui l'enferme) sont reduits à se changer en circulaires", Vol.21, p.255).

[143] (Vol.19, pp.632-4).

[144] (De la Cause de la Pesanteur. Vol.21, pp.379-382).

[145] (Vol.19, pp.199-215).

[146] (Vol.19, pp.634-6 and in 637, "Il y a une autre proprieté tres remarquable de la pesanteur qui s'explique encore par ce mouvement libre de la matiere a travers les spaces qui sont entre les parties des corps et qui malaisément le peut estre sans cela. C'est que toutes les parties du dedans d'un corps solide contribuent a sa pesanteur a proportion de leur grandeur; de quoy la raison est maintenant facile, quand on conçoit que la matiere fluide en passant librement par tous les endroicts de ce Corps agit par ce moyen sur toutes les petites par celles qui le composent et les pousse vers le centre de la Terre").

[147] (Snelders, H.A.M., Christiaan Huygens and Newton's Theory of Gravitation. Notes Rec.Soc. Lond.43, 209-222, 1989).

[148] (Vol.19, p.630).

[149] (Vol.19, pp.640-2).

[150] (Vol.19, pp.642-4).

[151] (Vol.9, p.377).

[152] (Vol.21, pp.445-7).

[153] (Vol.21, p.452).

[154] (Vol.21, p.453-6).

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[155] (Hutchison, K. What happened to Occult Qualities in the Scientific Revolution? ISIS, 1982, 73 (267), pp 233-267).
[156] (Vol.19, p.566).
[157] (Vol.19, pp.565-570).
[158] (Vol.19, pp.570-1), (On the observations on the microscope, Vol.13, p.708).
[159] (Registres de L'Académie des Sciences, T.IX, f.60 v.and T.X, f.180+, 1683).
[160] (Vol9, pp.574-8).
[161] (Vol.19, p.578).
[162] (Vol.19, pp.584-5).
[163] (Gilbert, Tractatus de Magnete, Lib.II, Cap.II).
[164] (Vol.9, to Leibniz, p.539, 572, Guericke's book Nova Experimenta Magdeburgica, 1672).
[165] (Hackmann, W. Electricity from glass: The History of the Frictional Electrical machine 1600-1850. Sijthoff & Noordhoff, The Netherlands, 1978, p.21).

[166] (Guericke, Otto von. The new (so-called) Magdeburg experiments of Otto von Guericke, 1672. Book III. Translated by M. Glover Foley Ames. Kluwer Academic Publishers, 1994, pp.114-161).
[167] (Dictionary of Scientific Biography, Vol.5).
[168] (E.W.von Tschirnhaus (1651-1709) studied at Leyden and joined the Dutch army. He worked in mathematics and physical experiences and was made a member of the Academy in 1682 and in 1690 was made a foreign associate whereas Huygens was not).
[169] (Vol.9, pp.124-147, to Leibniz 539 "je trouve les effets de l'ambre encore plus difficiles à expliquer que ceux de l'aimant").
[170] (Vol.9, p.552).
[171] (Heilbron, J.L. Experimental natural philosophy, in Rousseau & Porter, CUP, 1980, pp.357-387).
[172] (Vol.21, p.457).
[173] (Vol.21, p.458).
[174] (Vol.21, pp.466-70).
[175] (Vol.21, pp.471-2).
[176] (Vol.21, p.474, 476 "On a vû comment dans le Systeme de Mr Newton les pesanteurs, tant des Planetes vers le Soleil, que des Satellites vers leurs Planetes, son supposées en raison double reciproque de leurs distances du centre de leurs Orbes").
[177] ("pesanteur des corps, c'est l'action de la matiére fluide qui tourne", Vol.19, p.635).
[178] ("circulairement au tour du centre de la terre en tous sens par laquelle elle tend à s'en eloigner et pousser en sa place des corps qui ne suivent pas ce mouvement", Vol.19, pp.635-6).
[179] (Vol.21, pp.478-488 and Appendix I pp.489-93. Appendix II explains Newton's opinion on the Discours. He wrote to Fatio de Duillier, Vol.10, p.605, and general comments on Huygens' difficulty to agree with Newton's concept of gravity. However, Newton also had a problem trying to explain gravity as a mechanical effect, p.p494-9).
[180] (Ruestow, E.G., Physics at 17th and 18th century Leiden, "Joannes de Raey, 1656", Martinus Nijhoff, 1973, pp.61-73).
[181] (Vol.6, p.481, 327).
[182] (Vol.16, p.197).
[183] (Vol.16, pp.260-7).
[184] (Vol.16, pp.213-22).
[185] (Vol.10, p.614).
[186] (Vol.16, p.222, 226).
[187] (Vol.21 pp.818-821).
[188] (Yates, A. Giordano Bruno and the Hermetic Tradition, Routledge and Kegan Paul, 1978).

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[189] ("Réflexions sur la probabilité de nos conclusions et discussion de la question de l'existence d'êtres vivants sur les autres planètes". Vol.21 pp.541-567).

[190] (Piece II, Vol.21, pp.542-554).

[191] (Piece III, Vol.21, pp.555-9).

[192] (Vol.10, p.581).

[193] (Vol.21, pp.832-4).

[194] (Constantijn was secretary to King William III of Great Britain. Vol.21, p.680).

[195] (Vol.21, p.679).

[196] (Vol.21, p.680).

[197] (Vol.21, pp.682-5).

[198] (Vol.21, pp.682-3).

[199] (Vol.21, Book 2, pp.770-785).

[200] (Vol.21, pp.814-5).

[201] (Vol.21, pp.682-3).

[202] (Vol.21, pp.684-5).

[203] (Vol.21, pp.698-9, 798-801).

[204] (Vol.21, p.700).

[205] (Vol.21, pp.702-31).

[206] (Vol.21, pp.726-7).

[207] (Vol.21, pp.734-7).

[208] (Vol.21, pp.738-63).

[209] (Vol.21, pp.792-3).

[210] ("J'estime donc que chaque Soleil est entouré d'un certain tourbillon de matière en mouvement rapide, mais que ces tourbillons sont beaucoup différents des tourbillons cartésiennes" then he said that the planets were retained in their orbits "c'est la gravité ou pesanteur vers le Soleil". He referred to Plutarc's statement that the moon was kept in its orbit by the same force which made it flee away from the earth due to the circular movement and it was compensated by a force equal to the pesanteur by which it tends to come closer to it. Borelli also believed this and extended it to the planets. It was better explained by Newton "Isaac Newton a expliqué la même chose avec beaucoup plus de diligence et de finesse" Vol.21, pp.818-9).

[211] ("sur la nature de la gravité par laquelle les Planètes tendent vers le Soleil par leur propre poids, que le tourbillon de la matière céleste ne tourne pas autour de lui en entier en un seul sens, mais de telle façon qu'il se meuve de divers mouvements, fort rapides, dans tous les sens de rotation possibles à ses diverses parties, sans pourtant pouvoir se dissoudre à cause de l'éther environnant non agité par un mouvement de telle sorte ou de pareille rapidité" . And he continued: "je fais les espaces occupés par ces tourbillons beaucoup plus restreints que lui (Descartes). Dans la vaste profondeur du ciel je les suppose disséminés comme le sont de petits tourbillons dans l'eau, apparaissant ça et là dans un lac ou marais étendu, nés par exemple de l'agitation d'un bâton dans l'eau et fort éloignés les uns des autres. De même que les mouvements de ces petits tourbillons n'ont aucune influence les uns sur les autres et ne se gênent donc pas, ainsi aussi en est-il, pensé-je, des mouvements tourbillonnaires célestes qui existent autour des astres ou Soleils", Vol.21, pp.818-21).

[212] (Vol.21, pp.766-771).

[213] (Kircher, Iter Ecstaticum (voyage fantastique), Rome, 1656).

[214] (Bos H J M, Studies on Ch.Huygens, 1985, p.121).

[215] (Vol.10, p.297).

[216] (John Gribbin, Dark Matter and the Universe, New Scientist, 19 March, 1994, pp.2-3).

[217] (J. Glanz, Is the dark matter mystery solved? Science, February, 1996, Vol.271, pp.595-596).

CHAPTER 4

OTHER INSTRUMENTS IN HUYGENS' WORKS

The aim of this chapter is to show the diversity of interests that Huygens had when inventing and designing instruments. It will support my argument that Huygens was a pioneer in mechanical engineering. Some machines are presented without designs either because they have not been found yet, or Huygens did not bother to draw them.

As a very young scientist Huygens worked in different fields. Between the ages of 17 and 18 (1645-46), he studied, amongst other things, Archimedean geometry. Some of these propositions he improved and explained in his own way[1]. He expressed a constant admiration for Archimedes[2]. The influence of the Greek mathematician was very strong in the earlier years and all throughout his life. Huygens developed this method further and applied it mainly to mathematical studies, dynamics and the studies on optics, and to any theoretical explanation which accompanied his instruments.

In 1650, Huygens wrote a full account on the centre of gravity of floating bodies[3]. The same year Huygens drew his first machine for grinding lenses (see figure 1 in footnotes). Was this machine inspired by an Archimedean demonstration on the spiral?[4]. That year Huygens corresponded with Van Schooten, an ex-tutor, about using Archimedean geometry to demonstrate optical curves[5]. At the same time, he wrote about and constructed other geometrical ratios of circles and triangles[6]. In 1651 he published a treatise on the quadrature of the parabola, the hyperbola and the circle[7].

Although they were not as popular as the pendulum clock and the air-pump, Huygens designed a variety of other instruments: machines for grinding lenses, microscopes, telescopes, a planetarium, *carioles*, cylinders for gunpowder explosions and others. He showed ingenuity in the development of his own telescope, but it had too many pieces compared to the more manageable ones of the time. To make his model of planets moving around the sun, the planetarium, clockwork was incorporated. Not all of the instruments made between 1658 and the 1680s, had an associated mathematical theory, or led to the writing of a treatise. Instead they were the subjects of short manuscripts and drawings not intended for publication; some were not dated. The miscellaneous instruments included the level, a compass for use at sea, small water-skates devices[8], water-pumps and other gear-driven machines to improve the course of the Rhin and Yffel rivers[9], carriages (*Carioles, Calesche*)[10], or, improved designs for faster *carioles*[11]. It can be said that he worked on some of these following suggestions from contemporaries. This would be the case of his own drawings on gears and other water works in the early 1670-71, encouraged by his correspondence with Hudde[12], or, more imaginary ones, for instance, the water-skates.

The Huygens' brothers, Constantijn and Christiaan, were professional lens-grinders for many years. Their father pointed out in his correspondence that they had began in 1654 when they were in their early twenties[13]. They ground big lenses for the telescope and small ones for the microscope and the level. Their lenses were better than most. Although both worked with them, it was Christiaan who made important observations in astronomy and microscopy. Christiaan went further, bringing advances to the craft by designing instruments to grind standard lenses. Once again he improved the precision of instruments with designs of new parts and he developed a theory of optics to explain the reflection and refraction of the different lenses for both the telescope and the microscope.

His telescope was made up of more parts than others in use were at the time. He improved the different pieces, but observations were still difficult because there was no standard method by which the instrument could be set up exactly in the same way every time it was used. His lenses must have been very good because, as early as 1657, he discovered the satellites of Saturn, and was able to explain in his own way why rings were sometimes observed around this planet.

Huygens made two versions of the simple microscopes, those with a spherical hollow glass ball to observe transparent bodies; the other with a convex lens for opaque bodies. As for his compound telescope, it had two plano-convex lenses, which he thought yielded a better image. The various objects studied included dust, solutions of infusions, the tail of a fish, and little animals.

The miscellaneous instruments were sometimes accompanied by very little text. However, most of his devices were presented to the Académie des Sciences, for example, the clock, and air-pump. Huygens was obviously considered an inventor of machines at the Academy, because of the wide range of instruments and machines he designed. The latter included the machine to measure the speed of air, described in the previous chapter, also the telescope, and his drawings on water-works.

1. LENS GRINDING

Lens-making, according to some historians, was a gentlemen's hobby in the seventeenth century. I believe that it was indeed widely practiced by gentlemen and non-gentlemen alike. Christiaan Huygens was an example of lens-grinding for scientific purposes. He sold some of these lenses to contemporaries. He tried to make the best possible lenses for telescopes, microscopes, and the level. In his correspondence Christiaan complained about the lack of clarity observed in some of the lenses provided by craftsmen, suggested that lens-grinding could be profitable for those who improved their quality and made them by commission. This shows that there was another professional group emerging: the maker of scientific instruments, sometimes supported by the already long-established professional clockmakers.

Christiaan and Constantijn Huygens were well known lens-grinders[14]; the former especially was highly admired[15]. He gave advice to his contemporaries on how to improve lens-grinding[16] and sent his own and his brother's lenses to those who requested them[17]. I believe that for Christiaan it was an expertise job, which could be improved by the use of machines, and not only a pastime. Huygens designed elliptical and hyperbolic lenses[18] of different sizes, small for the microscope and bigger for the telescope[19]. Christiaan compared his lenses to others and claimed to have obtained better quality lenses than those made by Campani[20]. The big lenses for the telescope were used to observe the skies only after 1664[21].

1.1. A machine to grind lenses

Huygens drew and made machines to grind lenses as early as 1650 (figure 1 in footnotes)[22]. With them he could draw ellipses so that it was possible to delineate elliptical lenses on the glass, simplifying the task[23]. He accompanied these designs with geometrical explanations[24]. From 1660 until 1665, he designed bigger machines to grind bigger lenses[25]. In November 1664, Huygens used an iron disc to polish them, like Campani and Hooke, but maintained that the correct way to manage it was to put it over the glass and not the other way round[26]. This iron disc would have helped to perfect the final shape of lenses once the glass was cut to avoid lines in the glass[27]; Huygens used it on different occasions[28]. When comparing the quality of Hooke and Campani's glass lenses, Huygens preferred the Italian[29]. Christiaan and Constantijn soon made their own iron disc and used it from December 1664 onwards. Hooke had improved the iron disc[30] and Huygens recognized a change in the quality[31], still Huygens preferred his own. They also used two convex plates of leather on the glass blanks[32]. In January 1665, Christiaan was looking forward to seeing the lenses that the new machine would manufacture[33]. The design of the machines to grind big[34] or small lenses[35] were discussed by the brothers and improved[36]. More devices can be seen in the literature[37]. Christiaan' s machine was known to the Royal Society by the end of 1665[38]. He told Moray that he was perfecting it[39].

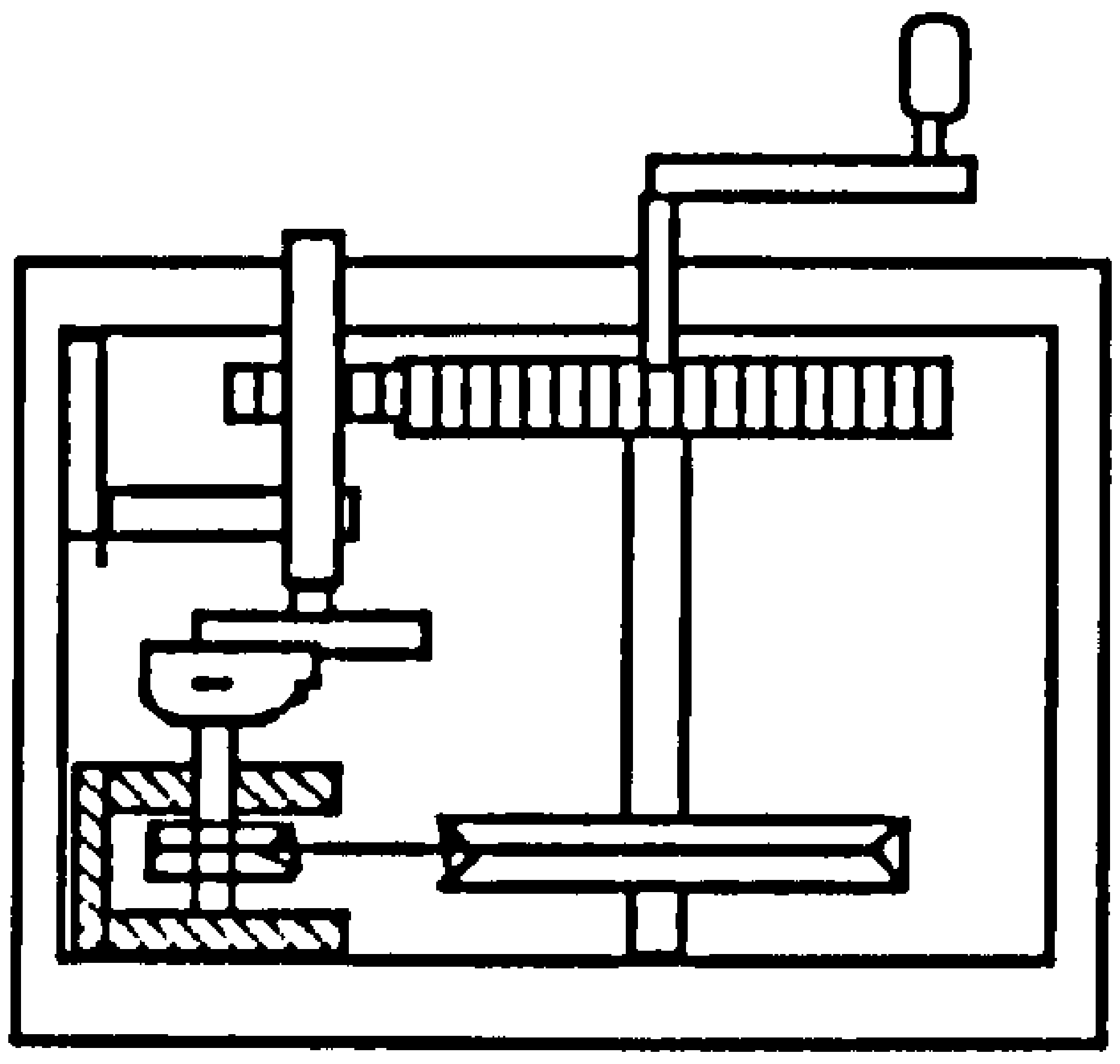

Figure 2 - Machine of 1665 to grind big lenses[40].

In 1666, Christiaan was mainly using his own machines to make big lenses because he commented on different ways of grinding a sixty-foot lens[41]. In 1670, Huygens speculated, because he had not used it, but only read the descriptions in two of Wren's essays[42], on the possible advantages and disadvantages of Wren's machine for grinding and polishing[43]. In 1685, both brothers were still perfecting the craft of grinding lenses. They used *morceaux de lime* for the final polish[44].

1.2. Materials used to grind lenses

Both brothers, Constantijn and Christiaan, were good lens grinders and worked together, especially, between 1650 and the early 1660s. Even when Christiaan was in Paris their cooperation continued by correspondence and, when he was back in The Hague[45]. Constantijn took an active interest in the lenses and in the instruments they used so that apart from grinding lenses well, he also understood the theoretical side. Christiaan was the natural experimenter of the two and the one who developed a body of propositions in optics. Already in 1652, Christiaan had deduced the theorem of the homogeneous sphere which could gather the incident beams of light in a unique point[46].

The two brothers had contact with several artisans who made lenses for them. Christiaan mentioned those who had worked on lenses for the telescope at the beginning. One was from Breda and made short-distance lenses[47], J.van Wijck de Delft[48], K/Calthof, or Kalthoven, from Dordrecht[49], Pain-et-Vin[50], and Meester Paulus[51]. However, the Huygens' brothers made many of their own lenses. This proves the fact that lens grinding was not an occupation unique to gentlemen; many craftsmen had been making them for years. They used different metals to grind them[52], as well as leather and plates of iron. Constantijn asked Kalthof to provide him with a model[53]. They worked regularly to perfect the lenses they were making[54]. Better lenses led to improved observations and helped to promote the understanding of dioptrics. Their technique was influenced, in 1655-6, by Kalthof[55], who was praised by the brothers as the great artisan in glass[56]. The glass was also carefully chosen and Huygens expressed his happiness when he secured it without air bubbles, or waves (*ondes*) of unusual thickness. In 1666, Huygens described the composition of the glass they were using and praised that from England as superior. He realized the importance of having the best quality glass and had some imported from England[57], from Lambeth[58], and he also used French glass[59]. His father brought back some samples from one of his trips[60]. As he did with his work on the clock, Christiaan passed on his own instructions to the glass workers (as he called them, rather than servants) on how to make the lenses for him[61].

In 1668 Christiaan ground lenses for microscopes[62]. During this time, he complained about how bad the quality of the glass was, compared to that from Venice, which he could get in Paris at Faubourg Saint-Antoine[63]. In Paris there were some good makers of big focal distance lenses, such as Menard/Mainard and son, who tried to find the right proportion of the eyepiece glass (*verres oculaires*)[64]. Menard was praised for his polishing methods[65]. Father and son worked for the Academy and the father died in 1669[66]. As engineer, Huygens designed and made a variety of focal length lenses: 35-, 40-, 60-[67], 100-foot lenses[68] and even a 120-foot[69]. In the 1680s, other lenses were made with an 8 inches (*pouces*) diameter[70] and a focal length of: 85-, 122-[71]; 200-[72]; 120-, 170-, 210-foot[73].

One of the French lens-makers mentioned was Lebas, who surprised Huygens when he showed that he could cut up to 10 or 12 glasses in his machine at one time, but who was secretive about his methods[74]. He worked for Huygens in 1672[75] and in 1675, Christiaan found out that Lebas also polished both, oculars and objectives[76]. An artisan was mentioned in 1673 who revealed a very complete method of grinding lenses to Huygens, perhaps Lebas. Christiaan mentioned other instrument makers who must have worked for him from the 1680s onwards namely: in 1683, Cornelis Langendelf a Dutch worker who cut glass for Constantijn and to whom Christiaan gave commissions[77], Dirck from The Hague[78], van Alsen a supplier of English glass[79], and Musschenbroek. Hartsoeker of Rotterdam exchanged correspondence with Huygens describing his own observations with the microscope and some optical geometry. He provided Huygens with small spheres of glass until Christiaan wanted to make even more perfect ones. Hartsoeker called himself an "instrumentmaker"[80]. This contradicts claims made by some historians who state that "instrument" was not a word in use in the seventeenth century[81]. Finally, Oosterwijk, clock-maker already mentioned before, was also a maker of microscopes[82].

They took good care in the manufacture of good lenses for telescopes and microscopes[83] to optimize observations[84]. In their correspondence[85] they discussed the importance of the physical properties of glass when making and polishing lenses[86], in particular convex lenses[87], and how to make them to a specific magnification[88]. Christiaan had a method of comparing how much different sizes of lenses affected the observations of each planet[89].

The method followed by Christiaan to correct the lenses was that of an engineer trying to achieve a perfect product by creating an instrument of precision and standardizing construction. Contemporaries asked him for advice on how to achieve quality lenses[90]. He looked for the best materials and tried known methods until he developed his own. He also designed his own machines for grinding lenses to obtain the best quality[91]. It helped him to predict the results judging by the effects his lenses would yield. All this is one more example of his role as an engineer trying to improve instruments with materials and by getting to know the best methods available with them. The amounts of lenses made and the variety of size, aperture, and focus[92], all of which were discussed in correspondence[93], further prove this. In 1656 Christiaan, apart from different sizes[94], worked out the convexity of lenses[95], without air bubbles so as not to impair the observation[96]. The small instruments he designed to make perfect elliptical lenses[97] also worked well[98].

In 1685 Huygens wrote a treatise: Memorien aengaende het flijpen van glasen tot verrekijckers, published posthumously,[99] about methods to grind lenses of long focus[100]. His biconvex lenses were quite symmetrical. Huygens explained how to design an instrument to make lenses and to polish them well. He designed the turntable to make the lenses with the best finished shape by making a plate turn over the other, and by using emery[101]. He also tried to help other lens-grinders in their task by giving a detailed explanation of the most important parts of the instrument to produce lenses with the best concave and convex curvatures. The way to choose the materials was also discussed. According to Huygens, good glass should reflect the light of a candle from the centre throughout the entire lens so that any lines, or imperfections, could be seen[102]. His detailed account also included the most basic principles. For instance, he drew two concentric circumferences, the central one with the required radius, whereas the external one, was used to grind the lens and explained how it should be further polished[103]. He knew that hand-grinding was difficult and slow for large lenses and also designed other instruments to grind big lenses[104]. Until 1692, Huygens continued improving different parts of these instruments[105].

2. OPTICAL INSTRUMENTS: The TELESCOPE, the MICROSCOPE and the LEVEL.

Huygens' studies in optics provided optical instruments and the grinding of lenses with a physical theory. These studies on optics did not get published, but they do reflect Huygens' methodical work, giving a theoretical explanation of optical instruments used for astronomical and microscopic observations. He described the relationship between the magnification of the lenses and what is still known nowadays as: Huygens' *oculaire* (eyepiece). Furthermore, in 1653, he developed three theorems on: (i) spheric aberration; (ii) chromatic aberration and (iii) the influence of diffraction on clearness. He worked on how to diminish aberration in the glass with the *oculaire*[106].

The Dioptrica of 1653, the treatise on refraction[107], had an important section on telescopes[108], and on microscopes[109]. Huygens stated how much better his telescope was compared to others, because the latter tended to lose a lot of light due to the thickness of the lenses. The field of view was enlarged with the use of only one eye lens and the images appeared less deformed. Moreover, he made all possible combination of lenses he could think of and saw by experience how useful they might be[110]. It is difficult to follow the exact chronology of this treatise. Huygens thought that the latter part of the Dioptrica[111] (on the biconvex lens of minimum aberration) was incomplete and wanted to improve this study for publication. He began writing it in 1653 and added new propositions and appendices up to the 1680s. It was almost complete by 1659[112]. By then, Huygens had introduced in the treatise a device for measuring the focal plane of the objective. He was still expanding it in 1692[113]. From 1672 until 1692, Huygens also worked on the catoptric lenses[114]. It described the optics of concave and convex lenses and their effect when used in telescopes and microscopes. It was divided in three parts. That makes it more surprising that historians such as G.L.' E . Turner have failed to consider Huygens' work on the microscope.

2.1. The telescope

Huygens, in his Discours de la pesanteur, unlike Descartes, did not believe that Jacob Metius was the first inventor of the telescope, but that either Lipperhey or Janssen was[115]. The lenses for telescopes were perfected regularly, and the sizes of the lenses discussed [116] and how the length of time used for observations could be increased[117]. The telescope was a long tube and its length was another factor Huygens changed to find the correct magnification[118]. The first theorem on magnification appeared in the Dioptrica[119]. In 1659, Huygens wrote to contemporaries interested in buying his ground lenses for use in their own telescopes[120].

2.1.1. The instrument[121]

In the Dioptrica, Huygens described the position of the lenses in the telescope. It should have two lenses in order to achieve the best vision: an internal lens, either concave or convex and smaller than the external one, which was convex. This model should be used for far away objects; to calculate the amplitude of the visual angle, and the aperture; or even to observe celestial bodies, if three lenses were used[122]. Huygens also demonstrated the construction of a four-lens telescope with, therefore, a vast field of vision, and a table telescope for use day and night[123]. The telescope was a measuring instrument for astronomical observations[124].

With some lenses the moons of Saturn were not visible[125]. He must have believed that one of the factors was to use lenses with a good finish in order to achieve better observations since he emphasized this so often. Huygens' telescope did not become as popular as Newton's. However, contemporaries recognized it as a very good telescope[126]. Therefore, they 'gave him' authority over the telescope, he did not take it from any contemporary astronomers as some historians have stated (van Helden, 1994). The first designs of this instrument appeared in Huygens' Correspondence as early as 1659[127], 1662, 1663, and the late 60s. He praised the work of some makers of telescopes[128]. Therefore, he recognized the role they played in constructing a good finished instrument.

As with the clock, Huygens designed several parts of the telescope in order to make it more precise. In 1658 he was designing the apparatus to support the telescope and the lens carrier[129] and redesigned it in 1659[130]. In 1680, he designed tubes to hold lenses to observe stars and measure the meridian[131]. In 1684, Huygens drew a new design of the telescope that he explained in a small treatise, the Astroscopia[132]. The distances between the lenses of the telescope, without the aid of the traditional long-supporting tube, became increasingly bigger in the 80s. In 1683 the distances were 34 and 36 feet[133]. Huygens' was an 'aerial telescope'. It did not require a long tube like those in common use. In 1684, Cassini wrote to Huygens about a new invention for the use of very big lenses. The former showed great interest in Huygens' telescope and said that it as the best built so far[134]. A year later, he made observations with a lens (*objective*) of 84 feet of focus supported by a mast of 61 feet[135]. In March 1687, he used a lens of 200 feet[136].

Huygens wanted to use bigger lenses but no tubes could be constructed to hold them. The various parts allowed him to make his telescope as long as he wanted and with the big mast a larger lens could be mounted. His idea was obviously unusual for that time since others continued with the one piece telescope. He believed that the observation would be better when using bigger lenses and a longer telescope. Hooke also believed that the longer the telescope the easier it was to see smaller stars[137].

The Astroscopia of 1684 was published in short form first, without the Addition. He sent a copy of it to some contemporaries: Perrault[138] and Cassini[139], because he thought this treatise would be better received in France. De la Roque published an extract from it in the *Journal des Sçavans*[140]. In it he explained some of the drawbacks when using this telescope, for instance, when there was wind. This amazed Huygens because people thought they would not be able to carry out observations in windy days when using the cord to focus. He believed that his method was good enough to become standardized easily[141] and pointed out that the invention relied mainly on the eyepiece (*oculaire*) and on an articulated arm with which the tube of the eyepiece could be raised or lowered[142].

As with the air-pump, the telescope, attracted a good many people who wanted to observe the planets through it. Huygens wrote in his Astroscopia that the telescope was set up in a way as to allow visitors to observe any planet they might want to see. For this purpose, Huygens had designed a special support for the observer[143]. And as with other instruments, the telescope was described in detail. Huygens made the telescope accessible to the public, thereby popularizing it; as he had done with longitude and his discussions with seamen.

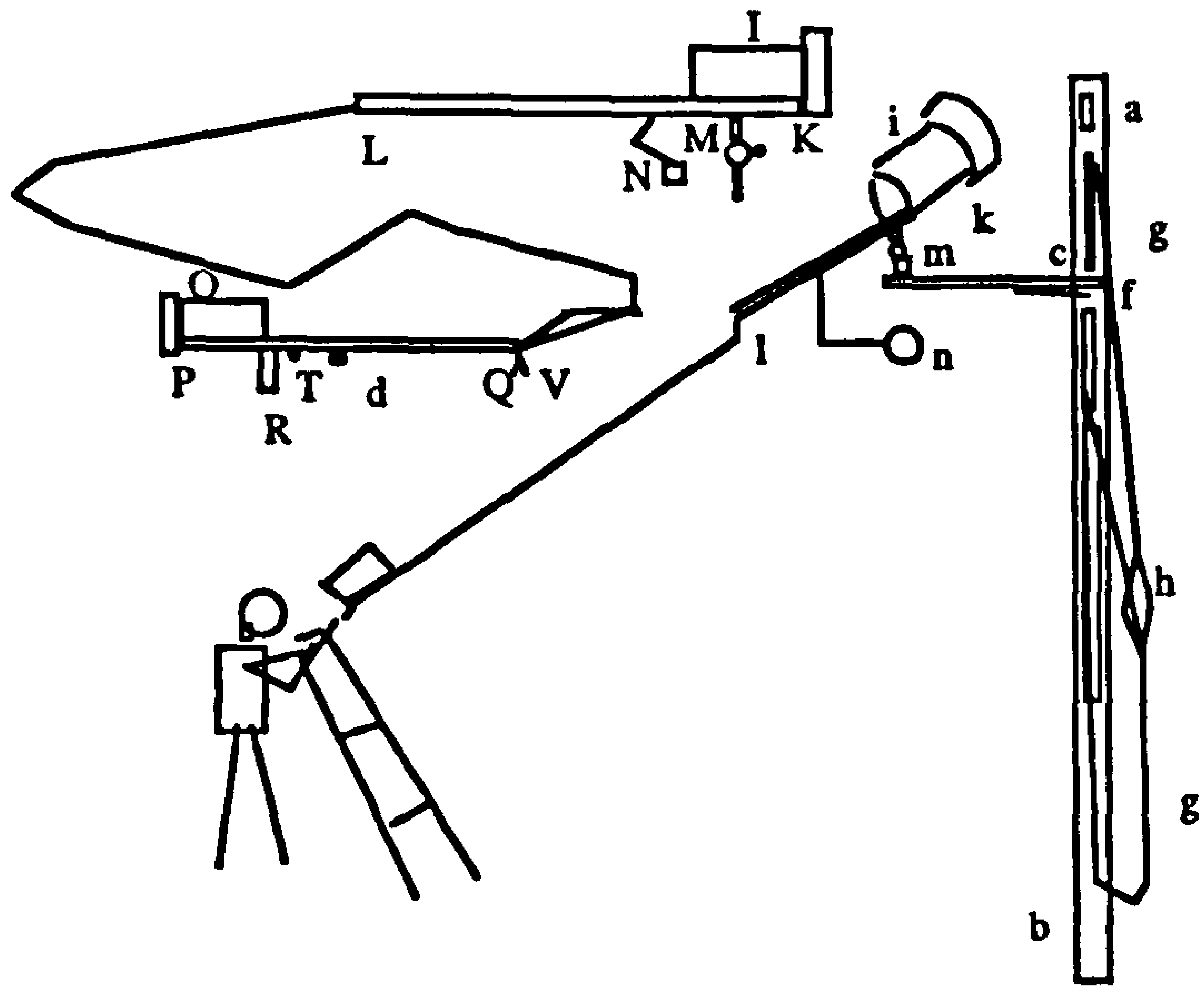

Figure 3 - Huygens' aerial telescope of 1684[144].

He described this telescope (figure 3) as follows: *ab* was the mast; *cd* the mobile runner; small shelf *f* carried the lens; *gg* was the cord; *h* the bob attached to the cord; *a,* the pulley at the end of the mast; cylinder *i* contained the main lens; *kl*, was the verge attached to the cylinder; *m*, was the small leather bob lining against the verge (*formant corps avec la verge*) and could turn in a spherical segment; *n*, the weight of lead; *o*, small tube with smaller lens (or *oculaire*); *p*, was the verge attached to this tube; *R*, the handle for the hand; *S*, a lead bob; *X*, the support for the observer;*Y*, was the lantern. The cord, which linked both lenses and was used for focusing, had to be straight and avoid curvature. One of the drawbacks of the instrument was the wind because it moved the focusing line, the cord. Although the length of the telescope, according to Huygens, did not matter, the height of the mast did[145]. The appendices to this treatise showed further drawings of possible ways of securing the lenses[146]. However, it took some time for Huygens to adjust everything. For instance, the mast moved on windy days and he decided to use three cords to keep it stable[147]. King has explained how the telescope was used[148].

Why did Huygens design this unconventional telescope without the usual long tubes and why did he not develop it further? In my opinion because it had too many parts, which introduced too many factors to be handled at the same time, making it difficult to manage. Moreover, to set them all up together must have been a slow process. Another important drawback was the weakness of the focusing line. This cord moved with the wind, so that observations must not have been very accurate in normal weather, and very difficult to perform in windy weather. However, for Huygens it seemed to be easy enough to handle.

2.1.2. The observations

Astronomical observations were an important topic in the correspondence of 1647 between Mersenne and Christiaan's father. Mersenne gave information on what was new about the telescope, its use and new models[149]. Already in 1648, Huygens was carrying out observations of the skies and reading the work of Kepler, Tycho Brahe, Hipparchus, Hevelius[150].

Huygens had a great regard for astronomy[151]. His contemporaries admired his observations[152] and some even wrote poems about them[153]. He discovered the new moon of Saturn as early as 1655. He attributed this to his design of a longer 12 feet telescope with 2 inches aperture[154] and a 23 feet one[155] and to his lenses, which allowed him to see the moons as well as the ring (see figure 4 in footnote)[156]. In 1656, Huygens wrote a small treatise on the new moon of Saturn[157] and its ring, which until then had been a problem for astronomers who had called this appearance, the arms (*anses*). Sometimes Huygens used this term, *anses*, when the ring was not visible in the centre[158]. He noticed an improvement in his observations because of the superiority of the telescopes he was using. He compared observations from year to year. The band appeared lower in 1656 than it had done in 1655 when he and his brother Constantijn made the first drawings of the planet and reported to have discovered the first moon of Saturn[159]. He defined the ring of Saturn as an: *"annullo, cingitur, tenui, plano, nusquam cohaerente, ad eclipticam inclinatio"*[160]. Huygens suggested that the month for the inhabitants of Saturn must be of 16 days minus 47 minutes[161]. He also made some general observations of Jupiter. All these observations were compiled in a treatise, the Systema Saturnium, published in 1659[162]. Dedicated to Prince Leopold, this treatise was highly praised by the learned[163], whose work he regularly mentioned in his correspondence, Wallis[164], Mylon[165], and Hevelius[166]. The latter promised to send Huygens the treatise he was working on about the wonderful observations of Saturn with the new lenses[167]. Roberval in 1656 also suggested explanations for Saturn and the new moon[168], and Colvius'[169] and Gassendi's observations of the planet were often mentioned[170]. Huygens sent communications about his astronomical observations regularly[171].

I agree with those historians who state that the Sistema Saturnium was a book on telescopic astronomy[172]. It was a comprehensive study of recorded observations. The aim was to explain the problem of the handle-like shapes observed on the sides of the planet. He described the ring of Saturn very elegantly. The ring was solid and inclined to the ecliptic. It was not attached to the planet, it was independent of it. He stated that some parts of the band, or ring, (*anneau*), appeared darker and this was due to the reflection of the sun in some areas of the ring[173]. A corollary explained why the ring was sometimes not visible. From a Saturnian point of view, those living on the equator of Saturn would be deprived of light because of the ring, here described as a thick and perfectly elliptical ring[174]. In this correspondence, contemporaries speculated on how thin the ring might be[175].

Between 1661 and 1665, Huygens observed comets[176]. In 1662-3, Huygens wrote a more general treatise, De Coronis et Parhelis, containing observations on the sun on the horizon and the crowns seen around it. This treatise shows a more general argument, without geometrical theories. He drew the observations in colors as well as those from other planets in the solar system[177]. For two years, between 1667 and 1668, Huygens observed different thickness in the ring of Saturn[178] and from 1675 to 1680 it started to appear as separated from the surface of the planet; most certainly because of the improvements introduced on the telescope over the years.

He continued his observations of the sky, sometimes with a colleague. On August 1668, Huygens and Picard observed Saturn. The latter recorded what they saw with a 20-foot lens and presented it to the Bibliothèque du Roy. Several articles derived from these studies[179]. They drew the planet and the ring visible on the sides but not at the centre where the planet was. The inclination of the equator and the inclination of the ring towards the ecliptic were measured several times: 9 degrees, and 23 degrees and 30 minutes[180]. These measures coincided with those of 1655, 1656 and 1657[181].

Giovanni Domenico Cassini discovered two satellites of Saturn, one in 1671 and a second in 1672. Furthermore, Cassini described spots on Jupiter and Mars and was able to deduce their respective periods. Huygens acknowledged these discoveries and praised them in the Dioptrique of 1683[182]. Cassini discovered two more satellites of Saturn in 1685, as he explained to Huygens in June[183]. Cassini used the superb telescopes of Giuseppe Campani and his contributions to astronomy transformed this field. Like all his contemporaries, Huygens admired Campani's telescopes and also those of Eustachio de Divinis. The new telescopes had become increasingly useful, especially, when they followed Huygens' innovating trend, after 1659, of manufacturing larger instruments[184].

The aim of the Systema Saturnium, was to maintain the harmony of the heliocentric system, as Copernicus had first defined it. Therefore, the right measures of diameters of the planets and distances between them had to be calculated with precision[185]. The concept of harmony was amplified in the treatise of the Cosmetheoros where Huygens presented four new satellites of Saturn with 170- and 210-foot telescopes and believed that still more escaped observation. Cassini shared Huygens' conclusion that the observation of the new satellites was difficult[186]. From 1680 until 1686 the observations concentrated on Mercury, Venus, Mars, on the distances of the planets[187], and on the atmosphere of the moon and the sun[188].

Huygens believed that his telescope must have been the best at the time because he was the first to observe the first satellite of Saturn. Since the ring of Saturn was a polemic issue, there was the question of whose observations reflected reality. Huygens suggested that his observation should be taken as standard against which others should compare their results. Saturn showed many different shapes, making it variable and unstable, it was difficult to find a common hypothesis to explain all these changes. Huygėns went as far as to suggest that, for forty years or more, astronomers ought to check the results on Saturn and compare them with his[189]. Armed with his observations and his theory of the ring, Huygens was convinced that his observations reflected what was there in the universe. Hevelius agreed with that because he believed Huygens' studies of the skies were reliable, whereas he had his doubts about what he saw through the telescope himself[190]. Huygens' telescope did not become popular as Newton's did. However, historians have failed to recognize how far he advanced astronomy if compared to contemporaries. He broke important traditional barriers, not only regarding the design of the instruments used, but also in the methodology and mode of observation.

2.2. The microscope

Spheric aberration was more important for the small lenses of the microscope than for the telescope. It became necessary to determine the distance between the eyepiece lens and the observing eye. Huygens' studies on the microscope were more detailed and interesting than is commonly alleged, except in the research carried out by Fournier in 1989. There were microscopes already in 1600[191]. Leeuwenhoek made one that worked as such and earned Huygens, recognition of his innovative priority[192]. Huygens was well ahead in observations. He drew what he observed with great detail, changing some of the factors to see how this would affect the images of the microscopic animals observed. He also designed and made several microscopes[193].

Huygens drew all the parts of one of his microscopes in 1678 (figure 6), and other variations of it (Fournier 1989). The source of light was a candle. Between 1683 and 1685 he described how to manufacture microscopes of small spheres of glass, how to mount them between two small pieces of bronze, and how to use them[194]. Another design, the two-piece microscope with a long tube was built in 1692 (figure 7, in footnotes). The 1692 design indicates that it could be used with sunlight or a candle since it had a slot and the user could modify the amount of light coming from either source. In my opinion, he must have built them all, otherwise he would not have developed his theory of optics for the different designs, also because he knew that the compound microscopes yielded a better image[195]. They were designed with two plano-convex lenses and the plane part of the lenses faced the object. He used them for the observation of opaque bodies. The combination of a spherical ball and a lens for the compound microscope was not advisable; the microscope would not produce a good image. Hooke said in one of his lectures, in 1679, that it was possible to obtain better images with the simple microscope as he had observed[196].

As Fournier has stated, Huygens' microscopes were widely known amongst the learned in France, and I would add in England and The Netherlands too. She describes different models of the 1678 microscope. Some designs of 1678 included a "diaphragm revolver and a specimen revolver". Several instrument makers copied them[197]. All the different designs were an improvement of the same instrument, which shows once more the engineer trying to find the best working device to yield better results. According to Fournier, these designs show that Huygens was seeking an image of high quality as well as an easier way to handle the specimens. But the really different model is that of 1692, which she fails to mention.

2.2.1. The instrument

The construction and use of the simple microscope (1654) is described in the Dioptrica[198]. Huygens created other types and continued until 1692 with modifications to the instrument and observations. The surviving drawings are only those of a simple microscope, but, according to his manuscripts, he fully described and showed how the other types would work. The simple microscope could be made with a spherical lens. He made some of these in 1658, 1660 and 1677[199], for use with transparent organisms. He used a convex lens for opaque bodies. The third type of microscope was the compound, with two plano-convex lenses[200].

Together with his brother Constantijn, Christiaan ground lenses and made microscopes in the workshop they shared as early as 1654[201]. Christiaan began his observations on the microscope at that time too and wrote about them in his letters to his brother Constantijn[202]. He did the same between 1678 and 1679. In this correspondence they exchanged new observations and new parts of the microscope, which Christiaan continued to improve[203]. Until the late 80s, they kept each other informed of their work on microscopes and telescopes. After this, the discussions on these subjects became more general. Constantijn did not seem to have the same inclination for detailed observations of the sky and microscopic animals as his brother had. Christiaan was the natural experimenter, whereas Constantijn was an example of a bureaucrat interested in the 'new science' in his free time. However, his work was of good quality; it was more than a hobby since he was able to discuss results and to understand Christiaan's work.

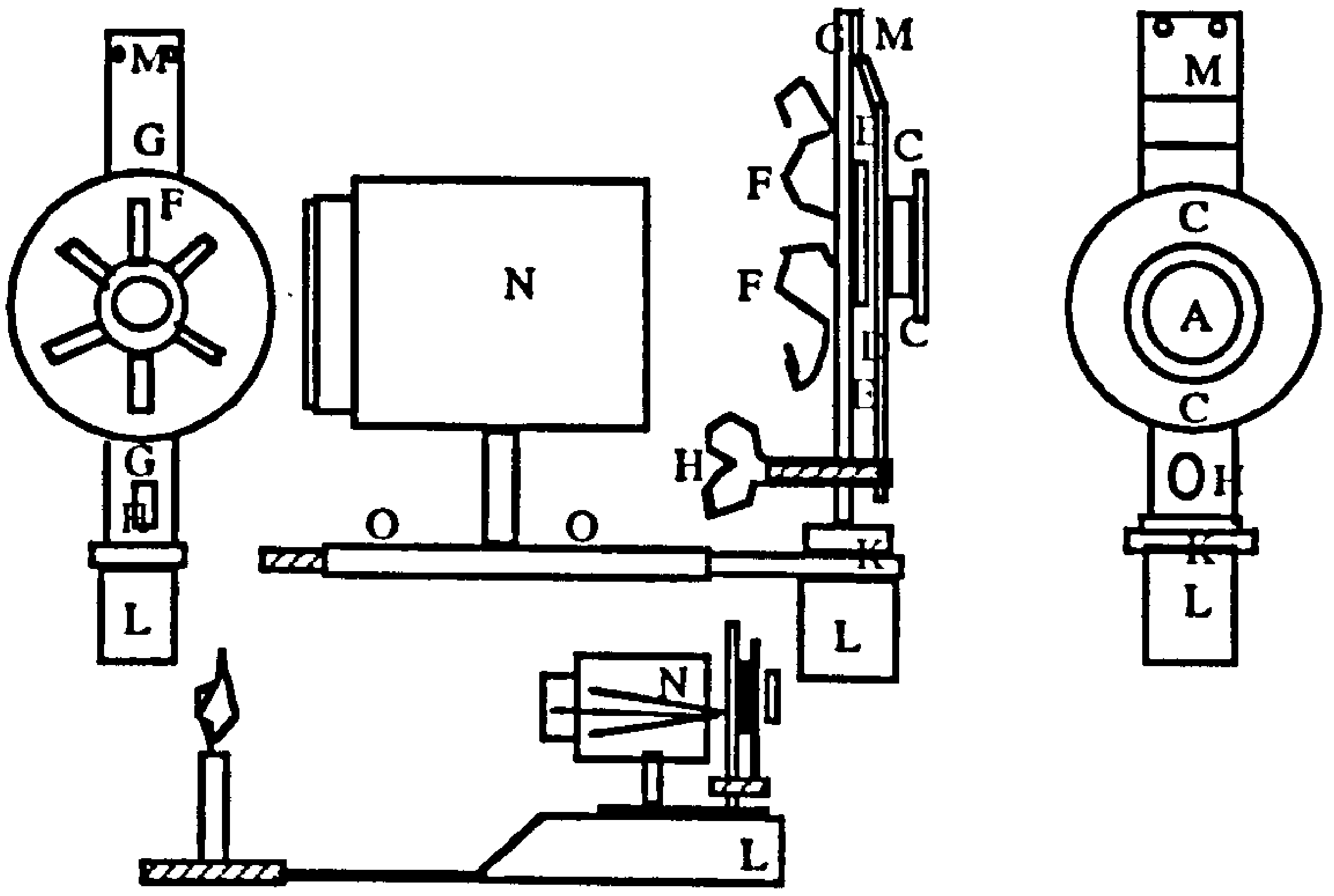

Figure 5 - The microscope invented in The Hague in May 1678[204].

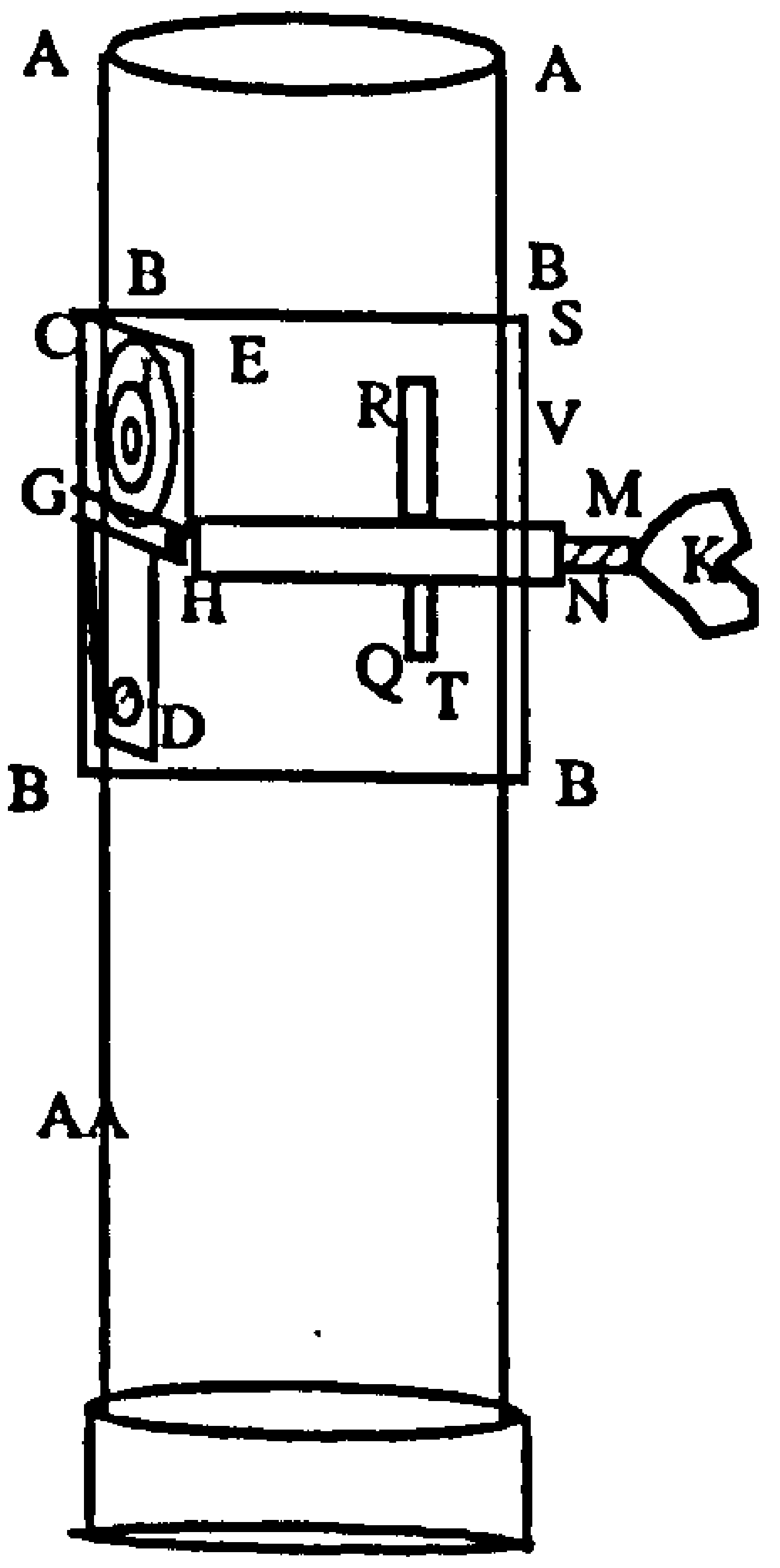

Figure 6 - The microscope of 1692.

This microscope (figure 6) consisted of two main pieces, the long cylinder AA and the shorter one which slided over it, BB. There was a much smaller piece attached to the cylinder BB with a nail, D, and which contained the plate DCE for the lens F. GH was a small device with two rings which acted as hinges to open plate CE. Cylinder BB was opened, the slot QR allowed the observer to have control over the light. The sample was placed in tube AA[205].

In this treatise, Huygens also drew a mobile lens to reflect the light from a source onto the microscope. The lens stood on a stand and was mobile because it was fixed to an axis (see figure 7)[206]. As an engineer, he compared two microscopes to calibrate them and recorded any differences in results. He found that with a constant magnification, the change of length did not seem to do anything, even when the focal distance was doubled. However, spheric and chromatic aberrations seemed bigger the longer the microscope. He tried again with two compound microscopes. He saw no difference between the use of a small lens and a sphere of glass[207]. He had used the same approach to calibrate clocks.

2.2.2. Observations

Furthermore, as an experimenter he knew how important it was to clarify the image in order to achieve better observations, and he worked in different ways to do just that[208]. However, he had to face the problem of spheric aberration that remained unsolved until 1692. He also realized there was a direct ratio between the magnification, the focus of the lens and the aperture. It was necessary to limit the aperture for lenses smaller than 0.5 inches of diameter[209]. It was more difficult to define aberration in the microscope than in the telescope because parallel beams could not be described in the microscope.

During 1674 and 1675, Christiaan became acquainted with Leeuwenhoek's observations, either through correspondence with his father Constantijn, or directly from Leeuwenhoek himself. Leeuwenhoek worked on preparations with different liquids. On the other hand, Christiaan criticized Leeuwenhoek for describing all his observations in the form of tiny spheres, whereas Huygens was able to draw more precisely what he saw, especially from 1679 onwards. Oldenburg agreed with this and suggested that maybe Leeuwenhoek' s sight was deceiving him[210]. It must have been difficult to draw conclusions about what they were seeing through this new instrument. They were observing completely new species of minuscule unknown animals, still unclassified because, until then, they had never been seen with the naked eye; and what was observed must have become more confusing as the magnification was improved.

Huygens' own observations with the microscope were fully documented with his own drawings from 1678 until 1692. He observed little microscopic animals, infusoria, from the solutions he prepared. He also observed spermatozoa, bacteria and parts of fish. He was inspired by Leeuwenhoek's observations of dust and other substances, but his observations were recorded in greater detail. Leeuwenhoek, followed what other contemporaries did and had the drawings made for him, especially when he had to send them to the Royal Society in London[211]. Huygens' drawings referred to everything he observed, spermatozoa, bacteria, parts of fish, rain water, solutions with dust, but above all to infusoria.

By 1678 Huygens recorded and wrote to Constantijn what he had seen on a preparation of dust and water. He observed a variety of small animals of different shapes and sizes. He made his own classification distinguishing those which appeared in the solutions (see A in figure 8, in footnotes) from the new ones, categorizing them according to shape and size (B-F in footnote). Some were transparent; others reflected the light because their skin was "full of little spheres which looked like shinny stones" (D). Others had a circular body with a big mouth and a long tail that attached itself to the surface of the preparation (E)[212]. The observations were sent to Leeuwenhoek to see if they coincided with what he had seen. Leeuwenhoek gave his opinion of each of these drawings to Christiaan's father, Constantijn, who passed these on to his son[213]. Constantijn expressed great admiration for this microscopist and suggested that many more people should be involved in this type of observations and the "discovery of things so beautiful would go very far indeed"[214]. This correspondence and admiration continued into 1679 and the early 80s[215].

In some of his observations of 1679, Christiaan acknowledged and agreed with his brother's Constantijn's studies on eels and other animals. The microscope was improved again. Constantijn did likewise. In August, the latter sent a selection of what he was observing. He reported to have seen great amounts of small eel-shaped animals, which he called insects, growing in a few days solution of dust and water. His drawings were similar to his brother's but he did not make so many divisions by shape, or size. Soon, Christiaan observed that the shape of a new small animal, he thought unknown, changed and was similar to a carp and gave advice to Constantijn on how to make a small platform to hold the specimen and the microscope to make it less tiring for the hand[216].

Huygens carried out further observations and more complete descriptions of microorganisms between 1678 and 1680, and in 1692. In contrast to what he had done in 1654, he recorded and drew everything he saw. In the early 1680s, while he was still working on his optical theory of lenses for both telescopes and microscopes, Huygens included some of the experiments carried out on animals: the tail of the eel and how he had seen all its veins, as well as the *animalcules* observed in drops of water [217].

His reports showed that he knew how to use the microscope and, most importantly, how to account for what he saw. This was a great achievement since in this formative stage of microscopy, there were doubts as to what was really there and how it was perceived through the microscope. Hooke, in the preface to his Micrographia[218], said that a change of light could yield a different image. This must have caused confusion for some time, making it difficult to decide how close to reality the observations were. Huygens expressed his admiration for Hooke's treatise in his correspondence[219].

However, Huygens seemed to have developed a standard way of observing. He compared microorganisms at different times of the day and under different types of light and intensities. He gave a full account of how the different factors affected microscopic observations. Time was one of these factors and he realized its importance in his tests. He took into account the time elapsed between the making of the solutions and their analysis under the microscope, and the different times at which the observations were made, as well as the variations seen. Another factor was the comparison between different solutions and microorganisms, as well as variations in the quantities of animals seen after several hours or days, and how differently they had grown in a variety of solutions and matrices. He compared the movement of some small animals in a drop of water to the movement seen with the magnet. This brought him to the cilia and the definition of other parts of the body of the infusoria in 1692.

Although Leeuwenhoek had already observed bacteria in 1675, Huygens went further and formulated his own theory on the origin of microscopic bodies. He did not believe in spontaneous generation of microscopic bodies, but thought that, attracted by odor, they originated from air. To prove this, in 1679 he began experimenting with dust and infusions in closed flasks. The results were not as expected. He found the same amount of animals in the closed flask as in the open one. Later, in 1692, he prepared a solution of water and dust in a tight bag of chamois leather. After three weeks there was hardly anything alive. He deduced that even those few animals might have got in through the pores of the chamois[220].

He used open and sealed flasks realizing that air might play an important role in the behavior of the small animals. It is clear that Huygens performed these experiments to show how these small organisms had originated. Nowadays it is known that some organisms might depend on oxygen for survival, whereas others do not. Huygens, saw no difference between an open flask or a sealed one, but this was because he had no way of knowing about the different species of microorganisms for which that change of environment would have made a difference. Microscopy was beginning and there was no understanding of what these small animals really were. They were still to be classified. Even less was known about their survival requirements, or any other characteristics. Nevertheless Huygens attempted a classification of some sort of infusoria in 1692.

Huygens fully appreciated the difficulties of observing and drawing transparent animals. These experiments might have encouraged him to make two types of simple microscopes. He preferred the simple microscope with a glass sphere for observing transparent organisms; for the opaque ones he chose the simple microscope with a small lens. Huygens' definition of a transparent organism was that the object intercepted the light but did not emit it, whereas in opaque organisms, the points of the opaque object radiated the light themselves[221]. It is my belief that he was able to produce drawings very close to what he was studying after carrying out the protocol created for his experiments and studying a different factor each time. His observations were also replicated and, therefore, followed a protocol by comparing drawings and results obtained from different solutions and periods of time. This helped to standardize the use of his microscopes. On March 1678, Huygens used a black base when he turned the microscope slightly on one side, so that the light fell on the side of the object. This exercise yielded a better shape of the bigger animals and sometimes a better image of the smaller ones. He experimented with heat and cold to see how freezing and boiling affected the microorganisms in infusions[222].

In 1692, he mainly observed the infusoria. These were of different species and he was able to record some of their characteristics. He found that there were two kinds: transparent infusoria and opaque ones. He drew and described the movement of the oscillatory cilia of the *Oxytrica* species. He described the external anatomy of Vorticella and their division and defined the exterior shape of the *Rotatoires* with a dorsal palpus (palpe dorsal). He also discovered the "viviparité de l'*Amguillula aceti*," a type of eel[223]. All this shows that Huygens' work in microscopy was more important than has been perceived.

2.3. The level

The level was another instrument designed and built to aid in navigation and in leveling terrain. Huygens claimed the invention of a new level made with lenses and demonstrated it before the Academy in 1679. It was published as the *"Nouvelle invention d'un niveau à lunette"*, in the Journal des Sçavans in 1680[224]. In 1675 Huygens acquired a copy of Picard's treatise on measuring the earth[225].

The level was easy to manage. If the liquid in it was in line with the horizon, the lead hanging from it would be perpendicular to it and directed to the centre of the earth[226] (see figure 6). It was essential to keep the lens in the centre, as well as the eyepiece (*oculaire*). Furthermore, it was very accurate and could easily be rectified. Like the engineer that he was, he drew the different parts of the instrument with specific dimensions and in perspective. The full account was sent to J.P. de la Roque on January 1680[227].

From 1668 until the 1680s, Huygens made a yet improved version of the level. In 1668 the level had a tripod support[228]. Later, in 1679, he explained the use of the level for measuring terrain, or surveying. He also introduced some changes in the instrument[229]. He stated that the advantages of using lenses for telescopes and other instruments to observe things closer also applied to the level. It made it a more precise instrument. The observer could assess better the necessary length of the cord that held the weight of lead used for leveling[230]. In 1679 he announced his new invention of the level.

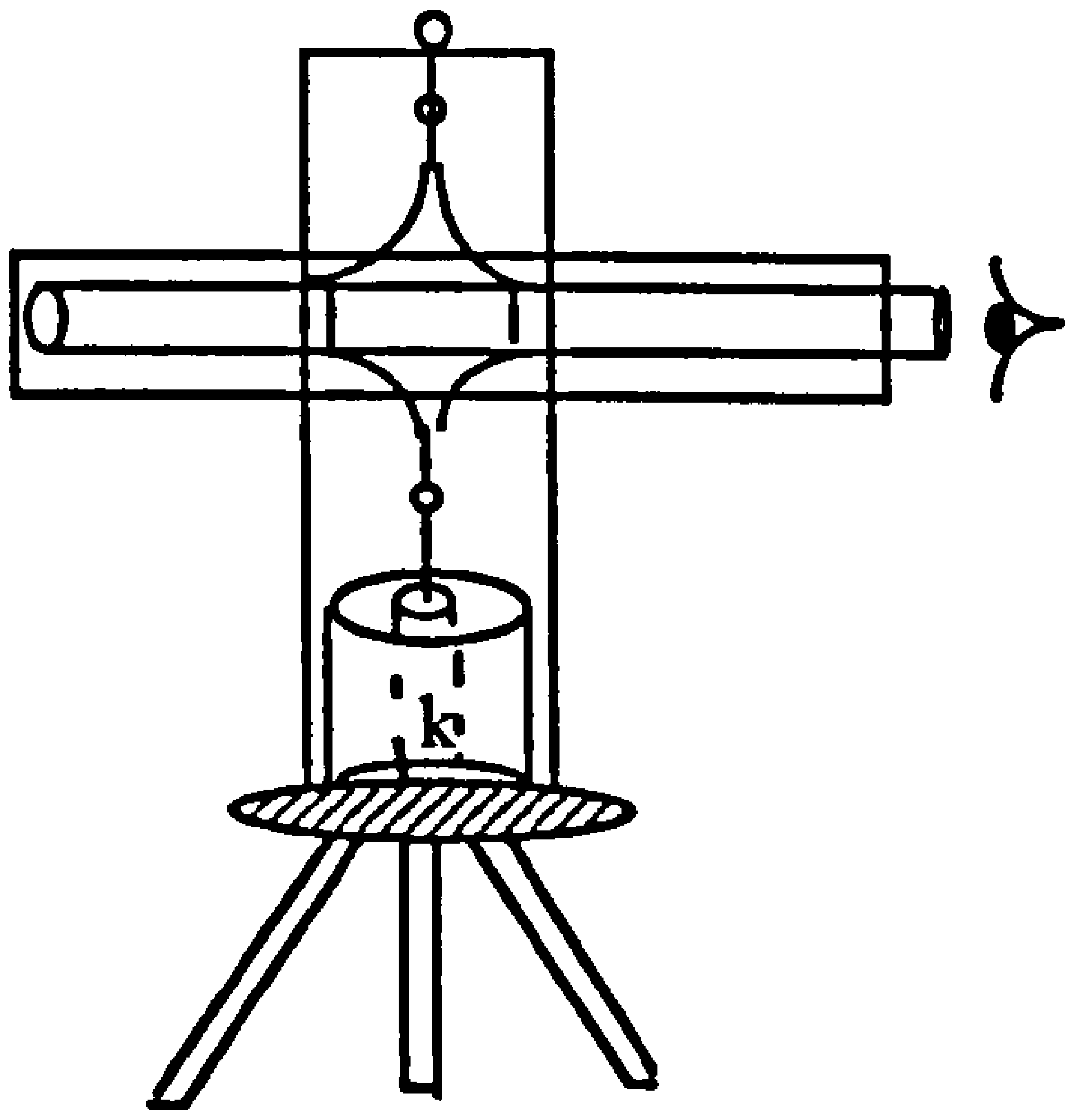

Figure 9 - Level of 1679. The vertical box contained the bob of lead, which remained vertical if the level was in the right position. The horizontal box contained the tube with the lenses and the observer's point[231].

The precision of his level was discussed several times in his notes and in his correspondence, where he explained he had changed the materials, from brass to other metals cheaper and lighter than the iron of the time. Other designs consisted of a prism inside the level. Four legs supported this prism, two sides of the prism could be opened[232]. As in previous instruments, the main objective when constructing and drawing was to achieve precision[233]. In 1693 some of Huygens' manuscripts show geometry applied to plans for leveling terrain[234]. This reflected, once more, the engineer trying to explain his instrument by an underlying theory and, at the same time, attempting to demonstrate how useful it was.

3. MISCELLANEOUS INSTRUMENTS

3.1. The Planetarium

In 1680 and 1681, Huygens studied the different velocities of the planets in their orbits, either elliptical or circular, and suggested different hypotheses for these variations. This was a small compendium of geometrical ratios of their velocities in orbit, and it incorporated a series of tables with the progressive fractions found. These fractions were the ratios of the pinions turning and the space covered by the planets and the oscillations of the pendulum[235].

Huygens, like other contemporaries, admired Ceulen's work on planetariums and commissioned him to build one according to his designs. Huygens often praised his work[236]. Colbert commissioned one and Huygens took it to Paris in 1682[237]. He designed a planetarium in 1680[238], and another one in 1682[239]. However, it appeared later, in the early 1690s, and was published in the Opuscula Postuma of 1703. Huygens said that he had thought of a way to use the clock to represent in scale the solar system and to work out the position of the planets[240].

Huygens described the planetarium, the automaton, in a letter to Colbert of August 1682. Huygens' had several advantages over those built by Römer[241], amongst other things because it he had represented the Copernican system with Keplerian proportions. The instrument had to simulate the right movements of those planets and to show the celestial archetype exactly. Once more Huygens talked of it as the *automati planetarii* . This automaton operated by means of a series of very simple wheels. Huygens' automata reproduced the orbits of all the planets and their satellites in the right proportions, which was lacking in Römer's. The periods of the planets were closer to the truth and with the method of continuous fractions he had found the right number of teeth in the wheels and pinions. Moreover, it represented the seasons and even the sunset and the sunrise, as well as the different shapes observed round Saturn.

The planets were made to run faster in their orbits the closer they were to the sun. The external form of the planetarium was an octagonal wood stand, with a diameter of two feet and six French inches thick. A glass over which he placed five planets with their satellites covered this stand: five for the moons of Saturn, four for Jupiter and one for the earth, and the sun. Around each planet he placed another sphere which represented the ether circling them. Finally, the ecliptic was the outer circle with the twelve signs and the 360 degrees marked on it. To find the place of a planet it was only necessary to use a thread from the earth to the planet [242]. To find the longitude another line parallel to it from the sun to the ecliptic was drawn. For the latitude, other circles had been built within the planetarium around the planets. The automaton was set in motion manually, using a small handle, it was kept in motion by the clockwork built into it. One revolution of the automaton was equivalent to the movement of one year[243].

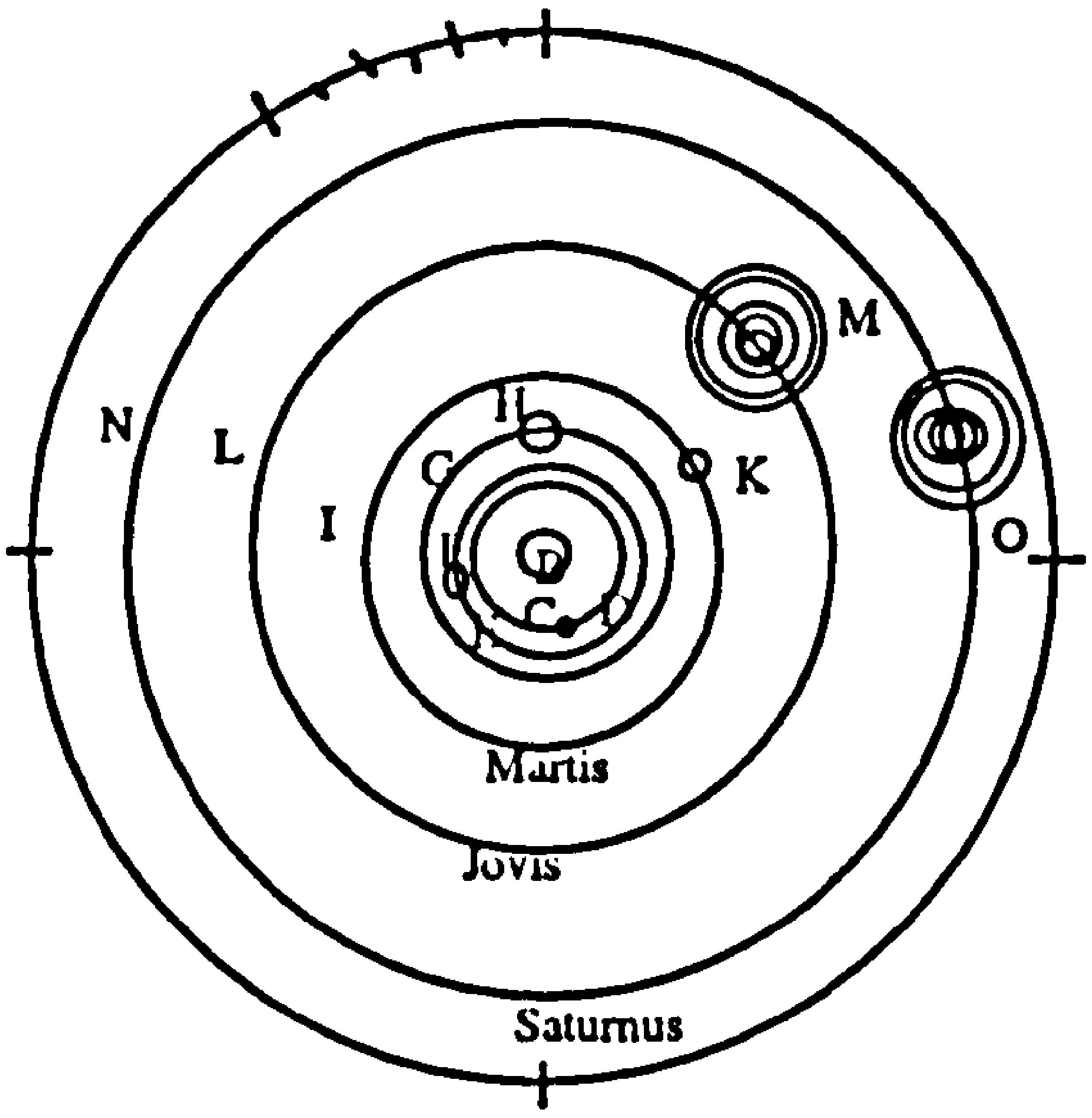

Figure 10 - Explanation of the position of the planets and the ecliptic.

In figure 10, B was the Sun; C was the orbit of Mercury; D was Mercury; E was the orbit of Venus; F was Venus; G was the orbit of the Earth; H were the Earth and its Moon turning around it; I was the orbit of Mars, K was Mars; L was the orbit of Jupiter; M was Jupiter with its four satellites; and N was the orbit of Saturn and Saturn was O [244].

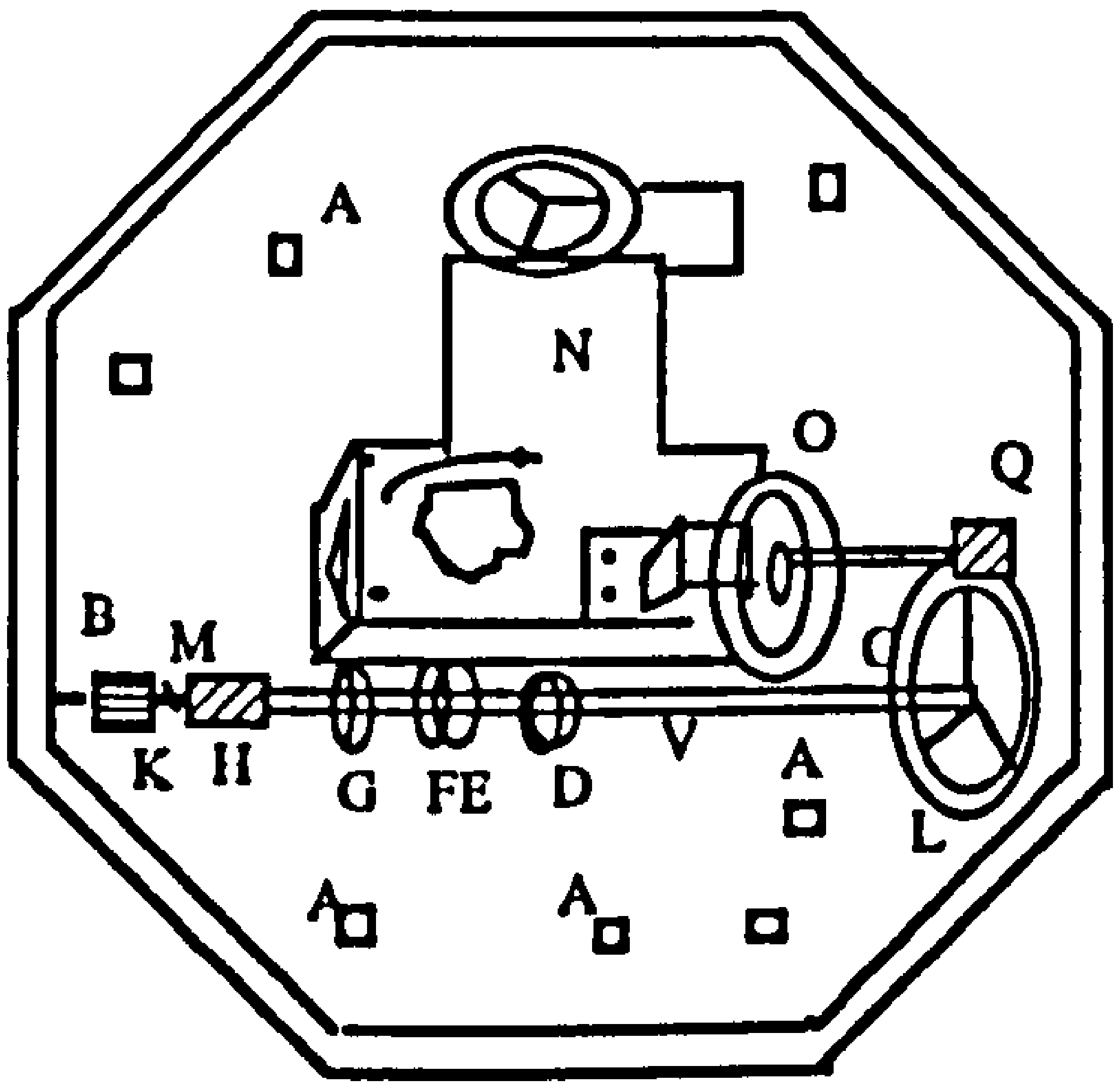

Figure 11 - Description of the machinery, which moved the planetarium.

In figure 11, points A were the points to which the rest of the planetarium was secured. BC was the axis of about two feet long. D was a toothed wheel of 121 teeth that moved the wheels of Mercury. E was the wheel for Venus with 52 teeth. F was the wheel for the Earth with 60 teeth. G was the wheel for Mars. Jupiter was wheel H with 14 teeth. Saturn had wheel K with 7 teeth and L was the wheel of 73 teeth for the circle over which the months and days had been inscribed. N was the clock. V was the wheel used to set the axis CB in motion[245].

The Discours included not only a full explanation of the function of each wheel upon which the planets were attached and their movement, but also examples of tables to calculate the position of each planet[246]. The machinery which made it work was fully drawn and explained (see figure 11). He did not think it necessary to provide a geometrical foundation to explain an instrument that was using the same machinery as the pendulum clock. Nevertheless, he used ratios to show the relation between the space traversed by the planets and the time elapsed. One of these planetariums is kept at the Boerhaave Museum (Leiden)[247].

3.2. Water pumps and fountains.

In the late 1660s Huygens copied the designs of a fountain from Colbert's garden. He thought it ingenious and made one similar but with more water. In the mid-1670s Huygens designed some fountains for the river banks of the Rhine and the Ijsel. In 1671 Hudde sent to him the drawings and map of where the works had to be carried out. In May Huygens and Hudde applied to the States General for an authorisation to supervise the water-works in those rivers[248]. The map built to scale had the points where the works had to be carried out[249]. Hudde also sent designs of the Hellegat and de Wildt rivers. His interests in water-works appear in the methods he suggested for the fountains in Versailles[250]. In April 1672, Huygens displayed yet again his engineering skills and designed some fountains, which were able to lift the water much higher than others of the time. These designs, together with those relating to his clocks, air-pumps, water-pumps, telescopes, and the gun-powder cylinder, were presented to the Académie des Sciences in the early 70s.

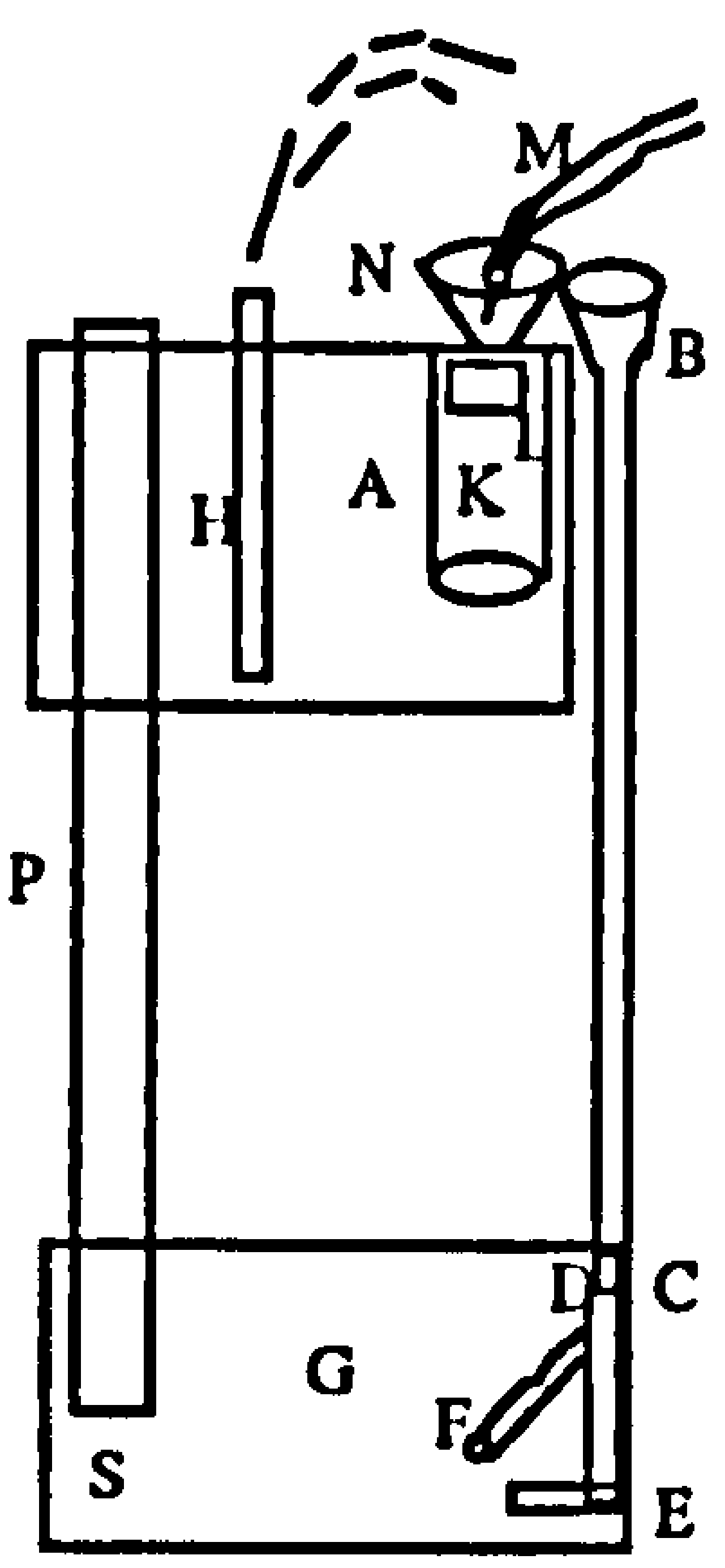

Figure 12 - Fountain designed by Huygens in April 1672.

The reservoir A was filled through N with the tube M. When A was full L floated blocking the tube. The rest of the water overflow over tube BC, cylinder CE descended blocking the tube in E. In turn, D, from tube DF, was opened letting the water in the reservoir G. Pressure was then created in G and also in A because of the communicating tube P, and the water erupted through H. This water was recycled through BC. More water could enter through M, and the whole process repeated itself continuously[251]. Huygens perfected the water pumps in the three following years[252]. Huygens, therefore, seems to have been employed at the French court for a variety of reasons. This is another example of Huygens as an inventor of machines accompanying them with a full description.

3.3. Gunpowder cylinder

Huygens invented a machine, which used gunpowder and vacuum to create a force capable of lifting stones, water, etc. The force produced could be exploited for purposes other than cannon. He calculated that a pound of gunpowder could give a force capable of lifting a weight of 3,000 pounds at least 30 feet. It would be useful for mines, building sites, fountains or any other task where human force or animal force was required "*on pourra l'appliquer a monter des grosses pierres pour les bastimens, a dresser des obelisques, a monter des eaux pour les fontaines*. This *moteur* could be applied to mills, where it would make the use of horses unnecessary "*a faire aller des moulins pour moure du bled en des lieux ou l'on n'a pas la commoditè ou assez de place pour se servir des chevaux*". Furthermore, it would be economical because it would cost nothing when it was not used "*et ce moteur a cela de bon qu'il ne couste rien a entretenir pendant le temps qu'on ne l'employe point*".

Several designs of this machine appeared in manuscripts of 1672 and 73, unfortunately there are very few of them with little explanation as how it worked. The aim of the invention was explained as follows (see also figure 13): "*L'invention consiste a faire sortir l'air d'un tuyau cylindrique comme AA, en y allumant dedans quelque peu de poudre a canon, pendant que le piston C bouche l'entrée dy cylindre qui de l'autre bout est fermé. L'air estant sorti par un trou qu'on fait quelque part dans le cylindre et qui se doit refermer aussi tot, le piston est pressè par le poids de l'air de dehors avec grande force, et par le moyen de la corde DD qui y est attachée il fait mouvoir ce a quoy on l'applique*".

The other end of the cylinder had to be attached to something stable so that it would not lose balance when the gunpowder was lit. The final aim was to release all the air from the cylinder, however, he was able to empty 1/6 of the total volume, with an output to 5/6 of what it could be otherwise, "*mais elle y laisse toujours environ 1/6 de l'air, ce qui fait que la force d'abord n'est que de 5/6 de ce qu'elle seroit, et qu'en suite elle diminue par de certains degrez qui sont aisez a determiner par le calcul et que l'on peut reduire a une force toujours egale par le moyen d'une fusee comme dans les horloges*".

Figure 13 – Gunpowder cylinder (See photocopy attached).

In figure 13, AA was the cylinder, B was the empty space, passage, of the piston; CC was the leather around it and DD were sponges to press the leather against the tube. EE were two plates to retain the sponges; FF was a small reservoir of water placed over the piston; GG was a plate to keep the water from overflowing when the gunpowder was lit; KK were used to stop the cylinder when the gunpowder was in operation; HH were two pieces of

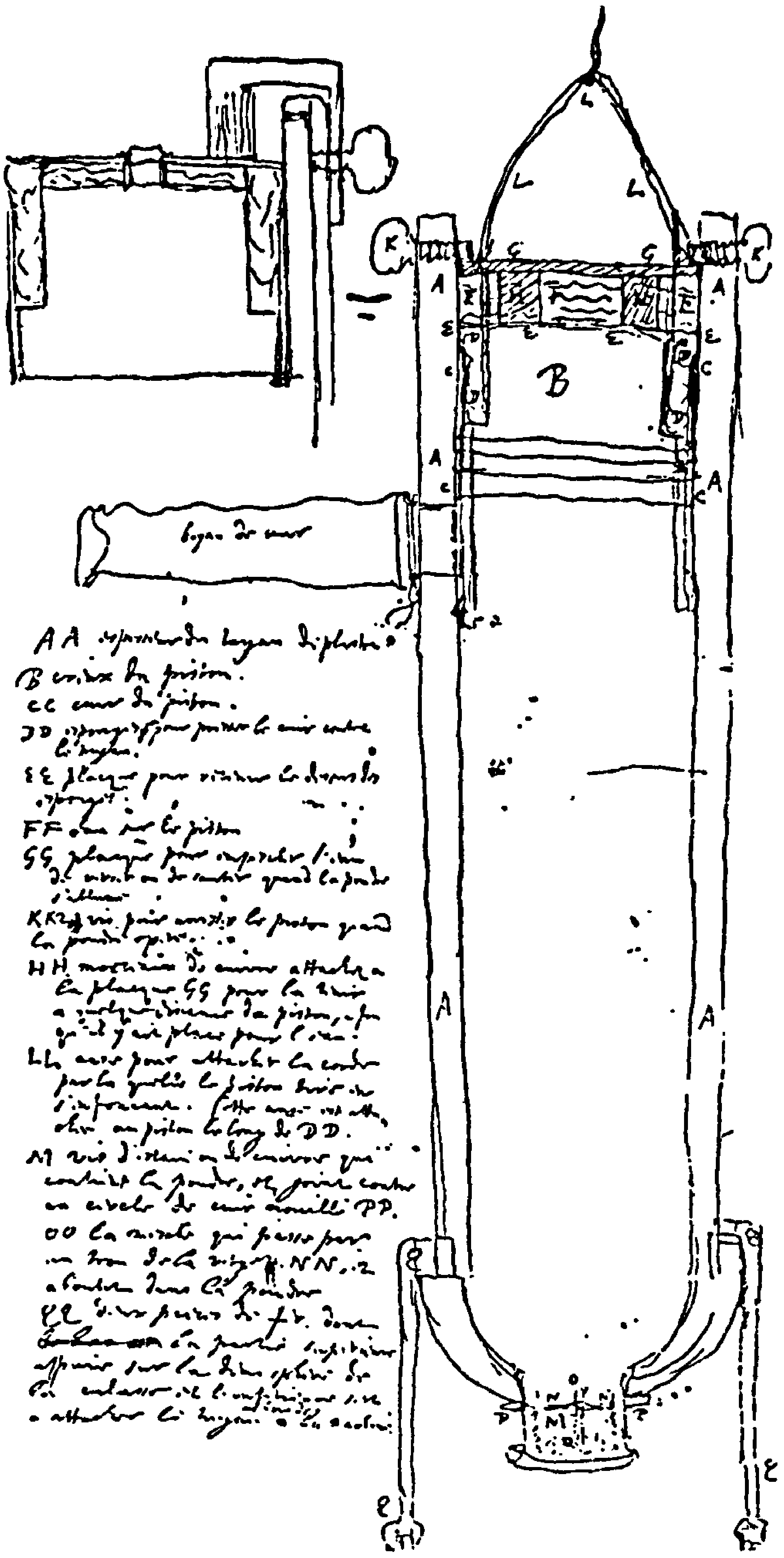

Figure 13 – Huygens' design of a Gunpowder cylinder.

leather attached to the plate GG to isolate it from the piston; LL was a handle to attach the cord which the piston pulled and it was attached to the piston along DD. M contained the gun-powder and was attached to the circle of leather PP. OO ended up in M; QQ were two pieces of iron to hold the cylinder and make it stable and they enclosed the box of the gun-powder. T was a tube of leather attached to an opening in A to allow the air of the explosion to leave the tube.

Huygens called the force created with the explosion of the gunpowder: moving force (*force mouvante*). It had a large number of applications. It could also be used to lift water and he concluded that the same kind of force was in operation in a big cylinder or in a small one. He stated that it could also be applied to move boats or other devices on land and to make all sorts of new cars (*voitures*) for water and land[253]. The machine was described in 1693 in the publication of Several works on Mathematics and Physics of the Gentlemen of the Academy of Sciences[254] as Huygens' new motor (*moteur*). Christiaan also described it to Lodewijk[255]. Christiaan seems to have invented the first gunpowder-fired engine, but it was too dangerous to use[256]. It also represented a new era of "engines" with many factors at play. By 1673, when using gunpowder and vacuum to create a propelling force, Huygens had already suggested that maybe the pressure of air created when gunpowder was lit in the void, could be used to make a *machine volante*[257]. However, no drawings have been found. Contemporaries such as Thévenot wrote to Huygens describing other machines in 1661. It was a *machine volante* that Buratini had presented to the King of Poland in 1648[258]. Huygens could not understand why a cord was needed to move the wings of this device. Instead he suggested the construction of an automaton, similar to that made by Architas, which would have the capacity to fly itself[259]. Maybe the *machine volante* Huygens had in mind was a kind of engine using gunpowder to set it in motion.

Papin, who lived at Huygens' house from 1673 onwards[260], continued with the experiments in the vacuum. I agree with Turner and Goulden that Papin was the inventor of the theoretical discovery of the steam-engine. He tried to obtain a steam pump following Huygens' work on the use of gunpowder to create vacuum in a cylinder[261]. Huygens did not pursue his experiments further, maybe because he did not know what to do to improve the efficiency of this *moteur* and did not understand the multiple factors it comprised, most of them unknown to him.

3.4. Carriages (*calesches, carioles, carosses, machine roulant, voiture*)

The practical use of Huygens' work can also be seen in his designs of coaches. The models of the 1660s must have been unpleasant to travel in since Huygens had felt sick, or feverish as he put it, after a trip in one of Colbert's coaches in 1666[262]. Huygens was determined to design one as comfortable as possible and the first drawings appear in 1662; he called them *Calesches*, *Carioles* (also *machine roulant or voiture*).

Before then, in 1662, Huygens was in The Netherlands and he maintained a continuous correspondence with French counterparts and knew about the new models being created by some aristocrats[263]. He may have designed some models already that year and, perhaps, even built some, because he wrote of the money needed to invest in their construction[264]. In 1663 he commissioned the building of a *carrosse*[265] and some were also made later in 1668[266]. In 1646, the king seems to have asked Huygens to design a carriage for two people[267]. He also advised other inventors on how to improve their models following Moray's suggestions; Silvester, a maker of carriages, was also mentioned[268]. Huygens tried these *chaises roulants* with members of the gentry and all agreed that they were much more comfortable than the ones in existence[269]. Moray asked the king for privileges and patents for the *chaise roulant* created by the Duc de Roannes and urged Huygens to try to get privileges for them also in The Netherlands and also for the *calesches* Huygens had designed[270]. The *chaise roulant* was smaller and faster than other models. The king found them very comfortable. These *calesches* were built and tested on long trips. Huygens received reports of how much better they were compared to earlier carriages[271]. Huygens wanted Moray to select one to be built in bigger numbers, including larger ones to carry people from village to village[272]. Huygens showed the mind of the engineer by trying to improve machines already in existence and by gathering information on trials from different models. Furthermore, he suggested their utility for larger numbers of people making, therefore, one more invention, which could have been of great use to the public. Once at the Academy, Huygens designed them with the aid of geometrical ratios, for instance, to show the weight carried by the horse versus that supported by the wheel[273].

Just as he did with other instruments, Huygens changed parts of the machine *roulant* to improve it[274]. His options varied from two wheels, as designed during the months of May and June of 1665[275], with a great economy of parts[276], to six wheels by 1669. From 1666 onwards Huygens designed them mainly in Paris where there were no restrictions on their use; they could not always be used in Amsterdam[277]. However, he preferred the Dutch coach-makers to the Parisians. The *calesches* he referred to in his correspondence were fully described with measures and materials[278]. They were lighter[279] and with better suspension than those in use[280]. Friction was also reduced as one of his models had proved while in operation[281]. Another builder of *voitures*, as he referred to them in 1671, was Bertholin[282].

The models could have more sets of wheels and were more *légère*, or narrower, than the coaches then in fashion[283]. He designed several types for his own use in 1668 and in 1669, with different drawings of two-wheel *calesches*, with good suspension and longer body to compensate for the stony roads so uncomfortable in shorter ones[284]. Huygens sent these drawings to several contemporaries[285]. Even in 1694 Huygens designed 2-seater coaches. They were very fast and easy to drive[286]. In some cases the wheels were found at the level of the axis of the horse AB, the chair was over a higher level (see -i- in figure 16). The other way round was designed in another model (see -ii- in figure 16)[287]. Huygens showed them to the *surintendant* of Coaches who was surprised with the design and Christiaan thought this reaction funny[288]. Maybe the superintendent found them too unusual and was really surprised at the models shown to him.

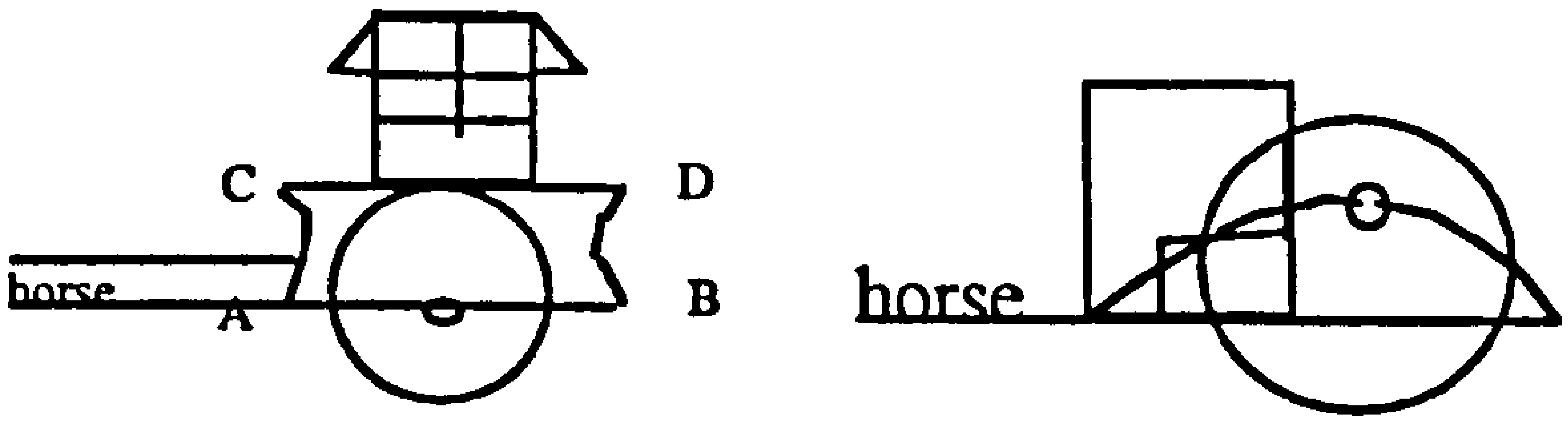

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Figure 16 - Coaches of 1666 and 1668.

Huygens' interest in inventing *voitures* continued during 1671[289]. In 1674 he invented a chariot with *planches* instead of wheels, but no design has been found so far[290]. Afterwards, no more designs of *carioles* appear in his manuscripts[291]. It could be that his new ideas did not appeal in the ambience of the court. They preferred to invest in what they already knew, not in new ventures.

3.5. Modification of Pascal's calculating machine (*machine arithmétique*)

Pascal's *machine arithmétique* consisted of a set of geared wheels. In 1660 and 1663 Huygens worked on the parts of this calculating machine[292]. His modifications to improve it mainly included wheels and rods. When in motion, each wheel moved a stick that in turn set in motion the drums. Each wheel had ten teeth and the next wheel began its motion as soon as the previous one completed its turn. Each wheel was designated for each decimal unit: units, tens, hundreds, and so on[293]. However, Huygens did not dedicate much time to this machine because it had already been invented.

Huygens received the first design and explanations of Pascal's machine in 1658[294]. The maker, Charles Bellair, explained to Huygens how it worked[295], but did not send the instrument until 1660. Huygens expressed his admiration for the device and its author[296]. He returned it in 1662, after Pascal's death[297]. Chapelain said that this machine was useful for addition, subtraction, multiplication and division and it was Pascal's wish to apply it to fractions[298].

3.6. Other devices

Huygens' position as a mechanical engineer is further supported by his interest in yet more instruments and devices. For some of these, only a few drawings are known. This is the case with the quadrant of 1685-6 (see figure 14). He said to have designed quadrants of different angles: 45°, 30° and 60° and others with degrees drawn on them. However, in the surviving manuscripts there is little more than their drawing and title.

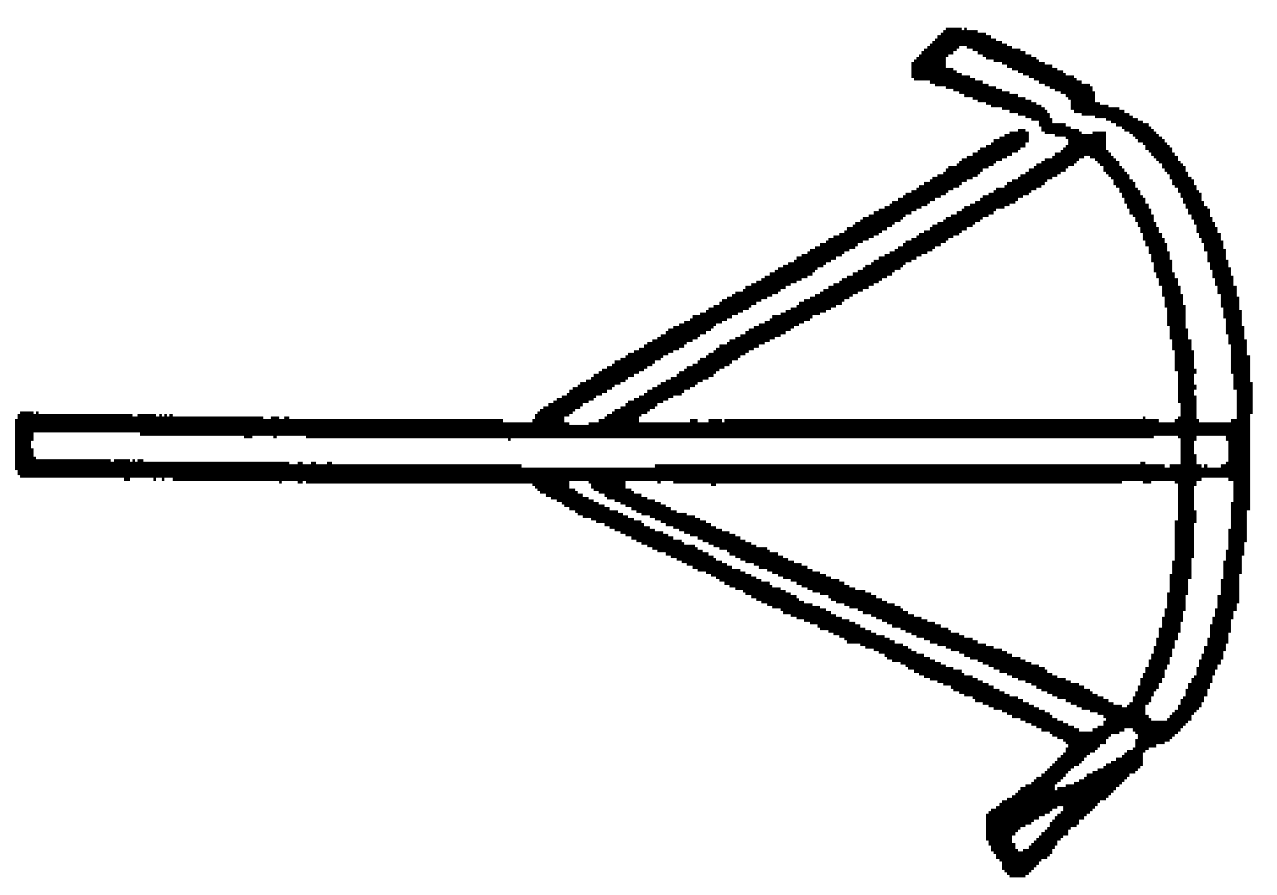

Figure 14 - One of the quadrants of 1685-6[299].

More imaginary and less scientific instruments, but still useful, include the water-skiing devices. At the end of 1658, he imagined a man walking on water wearing skate-like devices on his feet. These water-skates were supposed to serve either to push the boat or to be propelled by it (figure 15).

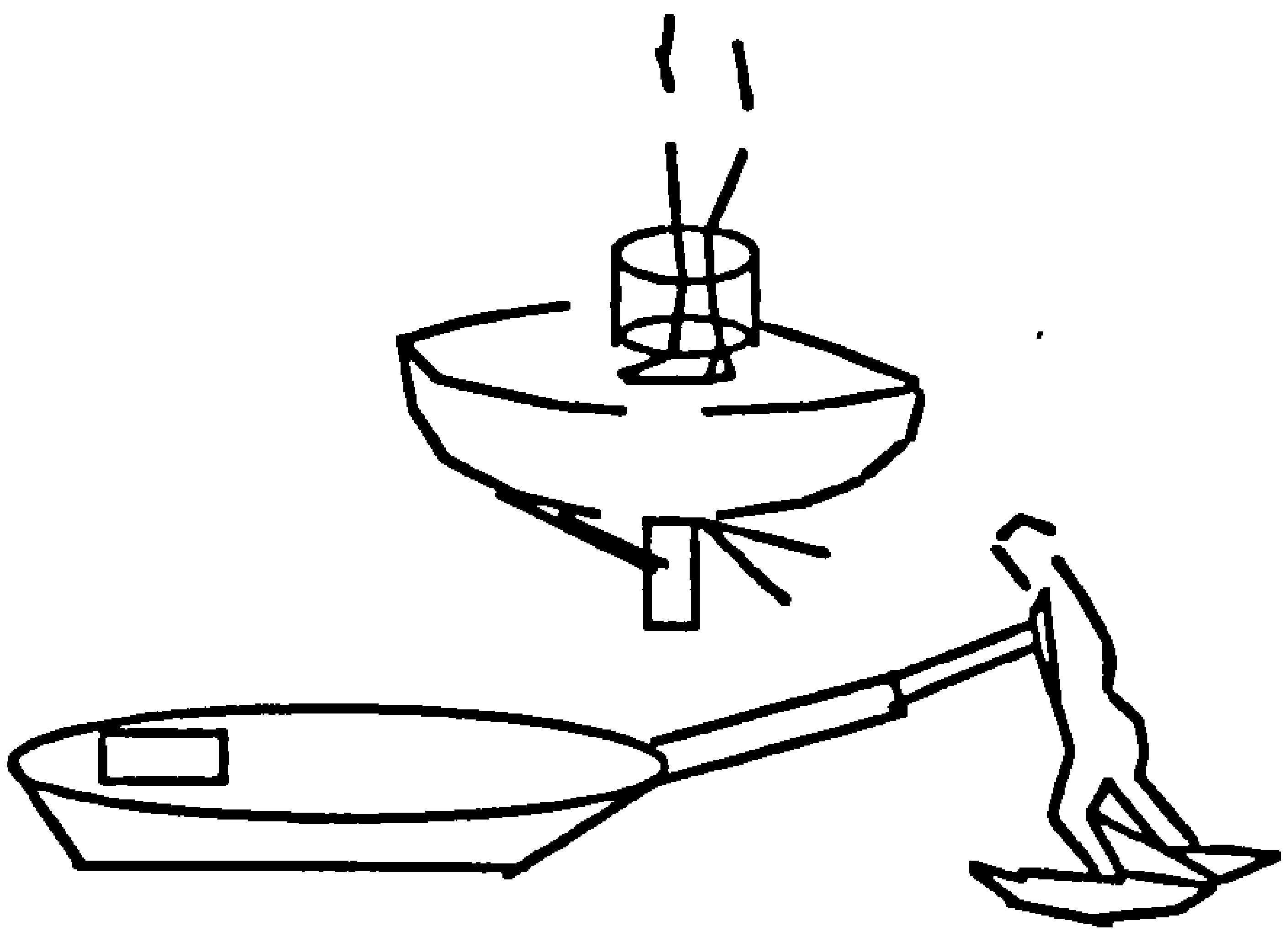

Figure 15- The skate-like devices for use on water.

With his keen interest in music, Huygens could hardly have ignored the musical box. He designed some musical boxes in 1673 and commissioned the instrument- maker Mans to make some. The drum of the musical box consisted of two wheels, one of which was toothed and turned on its axis between two small gear wheels[300]. This geared instrument was not accompanied in the text by geometrical ratios but some calculations have been found in earlier manuscripts dating from 1661[301].

4. CONCLUSION

The two brothers perfected the craftsmanship of lens-grinding. The engineer, Christiaan, realized that an instrument could do the grinding quicker, better and more uniformly than by hand. An instrument could standardize a slow and irregular manual process. Both brothers worked together grinding lenses and carrying out observations. Christiaan was scientific in his work and observations; Constantijn, understood his brother's work and carried out some observations, but did not develop any theories to explain the instruments they were using.

According to A. van Helden, Huygens' interest in astronomy was a consequence of his optical studies[302]. However, I believe that it was his genuine interest in different fields of knowledge that guided him to design the instruments he needed to improve his observations. Consequently, following his methodology he designed them and developed the theory necessary to explain the way they worked. Huygens' 20-foot telescope had been a turning point for astronomy in that he demonstrated that a much bigger lens and a larger telescope yielded better observations[303].

Huygens was a good observer and he exploited this talent well in any instruments that required persistence and a critical eye. The microscope and the telescope are examples of Huygens' method in science. He perfected them and developed a geometrical theory to explain how they worked. In the majority of cases this was with the support of the Archimedean method. This he did in fields as diverse as mechanics, mathematics, physics, optics, and cosmology. Huygens had been educated in many areas of knowledge. He soon acquired a methodology beautiful in its simplicity. It helped him to improve the instruments he designed and to analyze the results obtained from his experiments compiling them all in a treatise. All this was possible because Huygens was an innovator. His train of thought allowed him to make the right connections between experiments, observations and instruments.

His telescope might not have been an instrument of great influence. He did not get commissions from his contemporaries as he did for his clock. Nevertheless, he advanced the field of astronomy in two important points. First, with his discoveries of the satellites of Saturn as early as 1654, instrument makers and astronomers appreciated that with longer telescopes the smaller stars could be seen better. Helden states that Huygens assumed too much authority in claiming to have the best telescope. However, it can be said that Huygens "that relatively new-comer"[304] showed a rapid innovating mind. The model he created is a proof of this. It was the only telescope designed to be as long as the observer wanted. This was an important factor at the time because experimenters believed that a longer telescope yielded better observations. Secondly, the treatise System Saturnium presented a detailed method for astronomical observation and, it became a reference book for astronomers. His observations were a turning point in astronomy. Astronomy, for Huygens, was an applied science[305], which he admired above all others because it allowed man to observe such distant objects in the sky.

Historians have occasionally referred to Huygens' theories in optics only because of their errors, and do not emphasize the fact that Huygens' corpuscular theory, over the years, was preferred over Newton's wave theory[306]. There has been general lack of appreciation of his microscopy. I agree with G.L.'E. Turner that what was seen through the microscope was very difficult to explain and interpret for observers of the seventeenth century, as they themselves acknowledged in their correspondence[307]. They had to draw what they thought they saw[308]. However, Turner fails to mention Huygens. In my opinion, Huygens created a compendium of drawings of his observations and experiments, which are more than mere description. He had a standardized method of observation making his studies unique. He became aware of what was there to see and concentrated on obtaining a better image, making his own microscopes and designing protocols for his experiments. Accordingly these experiments were carried out with microorganisms and were replicated using the same solutions and over the same time intervals. Except for Hooke's Micrographia of 1665, this was not what most contemporaries did. Therefore, the doubts about what they were observing existed for them, but Huygens reduced this difficulty by creating his own method of working with small animals, especially the infusoria. He would not have arrived at this point had he not made a series of general observations and derived a reproducible test. He then knew what he was looking at; and he drew it. Furthermore, he compared his work with that of contemporaries: Constantijn, his brother, and Leeuwenhoek. Huygens was ahead of other experimenters because he integrated the observations with his own drawings, the instruments and their mechanical description in the same treatise. Good results could only be obtained with better or new devices which he designed himself.

This was an important contribution at the time and very advanced compared to other contemporary natural experimenters. Later, others filled in the gaps he had left and corrected propositions that were wrong. The main point is not so much trying to find what is original in a field of knowledge in a specific author, or what, some historians may think, has come down to us which is still used, as to see how far the author took that field of knowledge then. A minute proposition cannot be taken as the basis of a whole theory of optics, even if it is still used nowadays. This again is due to preconceptions. Historians should look at the past more objectively. It is essential to consider the additions made to the knowledge of the time in order to achieve a truer appreciation of Huygens's contributions.

Moreover, the fact that Huygens achieved good results on several occasions could be because he knew his instrument makers. He saw how important it was to know how to use and improve instrumentation. The skills of the operator could also affect the results. He chose good craftsmen who produced the highest quality instruments of the time and this added to Huygens' success with the pendulum clock, microscope, telescope, and other devices. They made better instruments because Huygens communicated with them and thought of them as collaborators. He knew what he needed and must have described it fully to the instrument makers. He appreciated who was the best in the field.

These inventions did not become scientific in the way we know them today until they were fully put into practice. Huygens was an inventor who, at the same time performed a series of observations or experiments himself, under the same conditions and compared the results obtained with others. When a conclusion was reached he deduced a theory for it. Huygens had a unique chance to show how a new field of science such as microscopy could be developed. He also took into account the quality of the lenses. He improved the instruments he used to make them more precise. He stated these basic factors, and contemporaries recognized them on account of his lenses, which many regarded as the best. He also described how and when to use the different lenses[309]. This became established scientific practice in the seventeenth century. He had advanced the field of observation with optical instruments, achieving an important influence in microscopy and telescopy. This was the result of careful dedication and repeated trials. And the comparison of his observations with those of some contemporaries allowed him to establish standardized methods of study in both these fields, with which other contemporaries compared their own results. This would not have happened but for the creation of new developing fields, such as microscopy, or the making of essential change to an astronomy in existence for centuries and showing a method for using the correct telescope to achieve the best results. But what was the social background to all this work? How were Huygens as a learned man and his inventions appreciated in the Court of Louis XIV? This will be discussed in the next chapter.

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[1] (Vol.11, pp.1-80).

[2] (Vol.1, p.161; Jan. 1652, p.170).

[3] (Vol.11, De Iis Quae Liquido Supernatant, pp.93-210).

[4] (Vol.1, p.115).

[5] (Vol.1, p.133, 134).

[6] (Vol.11, pp.216-269).

[7] (Vol.11, pp.281-337).

[8] (Vol.22, pp.194-6).

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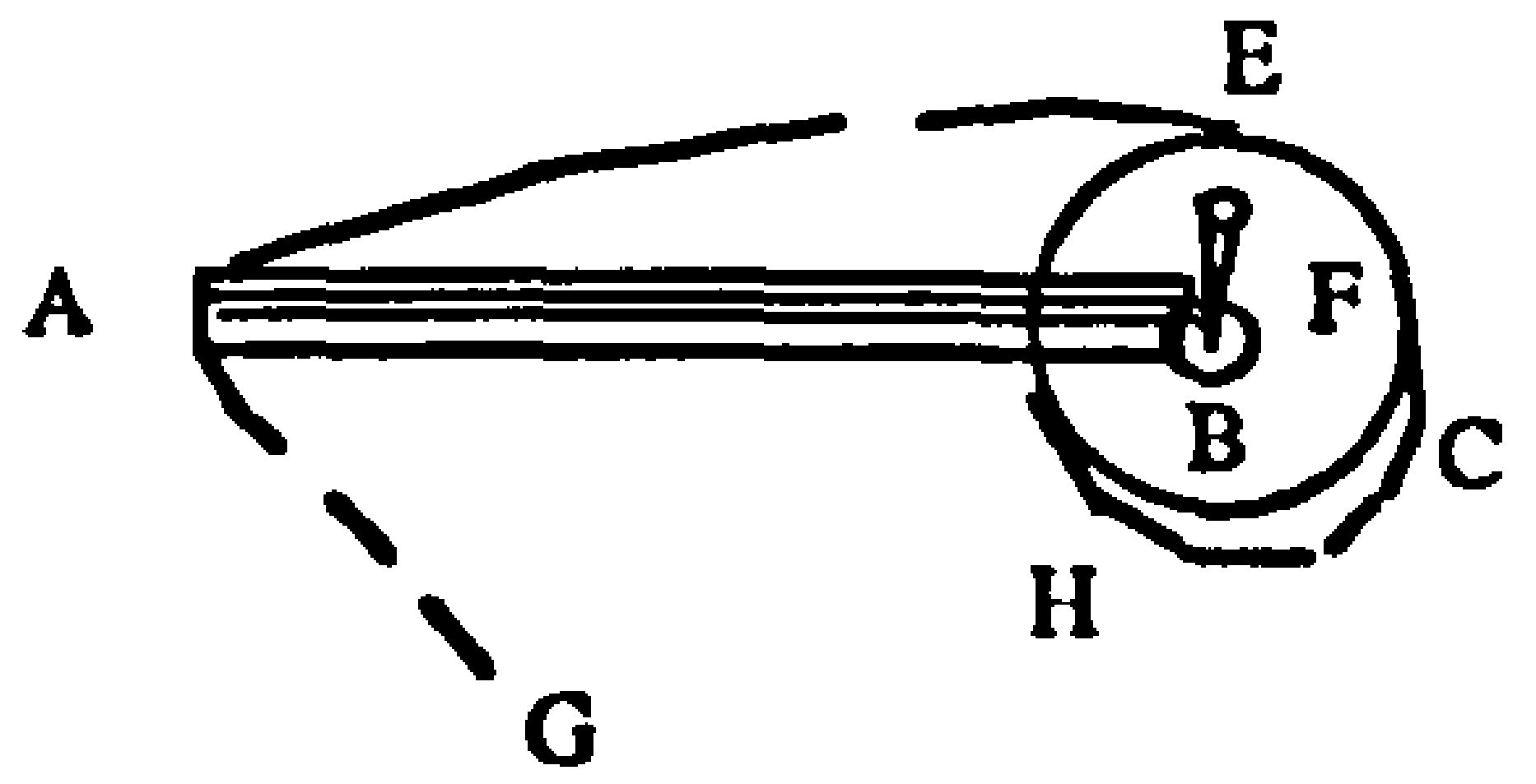
[9] (Vol.22, pp.284-9).
[10] (Vol.22, pp.277-9).
[11] (Vol.22, 1694, pp.322-3).
[12] (Vol.22, pp.282-9).
[13] (Vol.1, p.318).
[14] (Vol.2, p.66, 184, 186).
[15] (Vol.2, p.275).
[16] (Vol.2, p.273).
[17] (Vol.2, 1659, p.357, 361).

[19] (Vol.2, p. 273, 278, 319; Very large lenses, p.362. Vol.5, p.146).
[20] (1664, Vol.5, p.161).
[21] (Vol.5, p.64).



[22] (Figure 1 - F was mobile and the arm AB was attached to it, so that it moved around the fixed cylinder CH and the cord EAB with it. Vol.11, p.216).
[23] (Vol.17, p.287, 290-1).
[24] (The editor accompanied these manuscripts with footnotes giving a modern explanation of Huygens' understanding of the centre of curvature for the lenses he has in mind to design. Vol. 17, pp.288-9, 292-300.).
[25] (Vol.17, pp.301-4).
[26] (Vol.5, p.186. Hooke had described a circle of iron in his Micrographia of 1665).
[27] (Vol.5, p.148, 199).
[28] (Vol.5, p.130).
[29] (Vol.5, p.482; Vol.6, p.8).
[30] (Vol.5, p.148, 151, 152).
[31] (Vol.5, p.156).
[32] (Vol.6, p.87).
[33] (Vol.5, p.186).
[34] (Vol.5, p. 240, 241, 505; Vol.6, p.334).
[35] (Vol.6, p.205).
[36] (Vol.5, p. 550).
[37] (Gent, R.H. and Helden, A.C.van, Een Vernuftig geleerde, Museum Boerhaave, Leyden, 1995, pp.18-9).
[38] (Letter to Oldenburg, 3 Dec 1665, Vol.5, p.542).
[39] (Vol.5, p.550).
[40] (Vol.17, p.302).
[41] (Vol.6, p.23).

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[42] (Philosophical Transactions N.48, 21 June, and N.53, 15 Nov 1669).

[43] (Vol.7, p.3).

[44] (Vol.9, p.47, 591, 592).

[45] (Vol.1, p.355).

[46] (Vol.13, Book III. Or the modern term, focus).

[47] (Vol.1, p.295).

[48] (Vol.1, p.302 note of the editor: He grinded lenses for the microscope and the telescope and worked the metal for this purpose, p.352).

[49] (Vol.1, p.358 use of iron and other metals to do the grinding. Constantijn's answer: p.318. In November 1665, Constantijn said that Kalthof must be the first man in his trade in the country, p.360, 364; Vol.2, p.250-1,)

[50] (Vol.1, p.346).

[51] (Vol.3, p.215).

[52] (Vol.1, p.364, 387; Vol.2, p.251, 573).

[53] (Vol.1, p.355 and he sent it: Vol.1, p.375).

[54] (Vol.1, p. 380. Vol.2, pp.194-5).

[55] (Vol.2, p.251. Huygens wrote to Schooten: "I grind my lenses with 7 inches of diameter. They have been made like that by Kalthof").

[56] (Vol.1, p.364, 380-1).

[57] (Vol.3, p.277; Vol.6, p.533)

[58] (Vol.7, p.3).

[59] (Vol.3, p.398).

[60] (Vol.5, p.131).

[61] (1666, Vol.21, p.292).

[62] (Vol.6, p.158, 214, 219).

[63] (1667-9, Vol.6, p.148, 151, 158, 300, 533).

[64] (Vol.4, p.289; Vol.6, p.205).

[65] (Vol.6, p.152).

[66] (Vol.6, p.377).

[67] (Vol.6, p.460).

[68] (Vol.7, p.133).

[69] (Vol.21, p.259).

[70] (Vol.9, p.88, 590).

[71] (Vol.9, p.51).

[72] (Vol.9, p.88).

[73] (Vol.9, p.94).

[74] (Vol.7, p.311, 316-9).

[75] (Vol.7, p.480; Vol.8, p.241).

[76] (Vol.7 1675, p.485).

[77] (Vol.6, p.205; Vol.8, p.413, 415).

[78] (Vol.8, p.390, 411, 428).

[79] (Vol.8, p.341, 362, 385).

[80] (Vol.8, pp.58-61, 62-4).

[81] (A.Van Helden & T.L.Hankins, Instruments, Osiris, Vol.9, 1994, pp.1-6).

[82] (Vol.8, p.89).

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[83] (Vol.1, p.201, 384, 425).
[84] (Vol.1, pp. 205-6, 471).
[85] (Vol.1, pp.221-3).
[86] (Vol.1, pp.224-6).

[87] (Vol.1, p.346).
[88] (Vol.1, p.318).
[89] (June 1673, Vol.7, p.310).
[90] (1665, Vol. 6. pp.346-7).
[91] (Vol.6, p.482).
[92] (Vol.6, pp.299-300).
[93] (Vol.1, p.363).
[94] (Vol.1, p.338).
[95] (Vol.1, p.384).
[96] (Vol.1, p.220).
[97] (Vol.1, p.386)
[98] (Vol.1, p.393).
[99] (Vol.9, p.591, and in Vol.21).
[100] (Vol.21, p.259).
[101] (Vol.21, pp.254-7).
[102] (Vol.21, pp.262-5).
[103] (Vol.21, pp.264-279).
[104] (Vol.21, pp.280-292).
[105] (Appendix III, Vol.21, p.293, 300-1. Vol.21, pp.300-1).
[106] (for a summary of Huygens' optical laws, see the editor's preface to Vol.13).
[107] (Later, in 1679, Huygens presented some of his works on optics and on refraction at the Academy, Histoire de l'Académie, Vol.1, pp.283-290).
[108] (Vol.13, pp.1-511).
[109] (Vol.13, pp.512-585).
[110] (Proposition III, Book III, Vol.13, pp.252-3).
[111] (Vol.13, pp.434-585).
[112] (Vol.13, pp.737-807, 820-844).
[113] (Vol.13, pp.737-802).
[114] (Vol.13, pp.803-819).
[115] (Vol.13, pp.436-7, 586, 588, 591-93. Helden, A. van, The Invention of the Telescope, Trans. Amer. Phil.Soc. 67. 4. 1977, p.5, and by the same author: The Historical problem of the invention of the telescope, Hist.Sci. 1975, Vol.13, pp.251-263).
[116] (Vol.1, p.381. Vol.2, p.362).
[117] (Vol.1, p.383, p.481).
[118] (Vol.1, p.488, p.511).
[119] ("The magnification of a lens is equal to the quotient of the focal distances of the two lenses" Vol.13, p.193, 197)

[120] (Vol.2, pp.362-3).

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[121] (Huygens used the term in 1659, Vol.15, p.212. Most discoveries were made with telescopes well under 100': Rudd, M.E. The long and the short of it: telescopes of the seventeenth century. Journal of the Antique Telescope Society. 1993, Vol.4, pp.12-19).

[122] (Prop.I, Vol.13, pp.442-451; Prop.II, pp. 450-3, Prop. VII, pp. 480-499; Prop.IV, pp.460-7).

[123] (Vol.13, Prop.V, pp.468-473; Pro.IX, pp.502-511).

[124] (Bennett, J.A., Christopher Wren: Astronomy, Architecture and the Mathematical Sciences, Journal for the History of Astronomy. Vol.6, 1975, pp.149-184).

[125] (Vol.1, p.424).

[126] (Chapelain to Christiaan, 1656, Vol.1, p.437).

[127] (Vol.2, p.362-3).

[128] (Vol.15, "Brevis Annotatio in Systema Saturnium").

[129] (Vol.22, pp.181-193).

[130] (Vol.2, pp.362-3).

[131] (Vol.21, p.56-9).

[132] (Vol.8, p.488).

[133] (Vol.8, p.475. Vol.15, p.145).

[134] (Vol.8, p.482).

[135] (Vol.15, p.156).

[136] (Vol.9, p.125).

[137] (longer and better telescopes help to "discover to us smaller and smaller fixed Stars", Hooke, The Posthumous works of R.Hooke, 1969, p. 77).

[138] (Vol.8, p.531).

[139] (Vol.8, p.492).

[140] (Lundy, 4 Dec. 1684 the Journal des Sçavans. Vol.8, p.488, 496-7).

[141] (Vol.8, p.525).

[142] (Vol.8, p.497).

[143] (Vol.21, pp.202-9).

[144] (Vol.21, pp.218-221).

[145] (Vol.21, pp.210-231).

[146] (Vol.21, Appendixes I, II p.232-236. The telescope could magnify about 50 times with half a degree of field view and twelve feet long. Bos.H.M.J.et al edit. Studies on Christiaan Huygens, Alan van Helden, Huygens and the astronomers, p.148).

[147] (Vol.9, p.51).

[148] ("A groove running up the mast enabled the lens mount, counterpoised by a lead weight, to be either raised or lowered. The lens carrier was mounted on a ball-and-socket joint, operated from the ground by means of a connecting thread or string and reached, when necessary, by a series of triangular steps. An eyepiece supported by two wooden feet and attached to the free end of the thread received the image produced by the lens. The observer balanced his arms on the wooden rest and held the eyepiece with one hand. The length of the thread not only indicated the position of the focus, but, when taut, aligned the object-glass with the eyepiece" King. G. The history of the telescope, Dover Publications, N.Y.1979, p.54).

[149] (Vol.1, p.48).

[150] (Vol.1, p.85).

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[151] (Vol.1, p.335).
[152] (16th Sept. 1654, G.A.Kinner a Löwenthurn to Christiaan, Vol.1, p.297).
[153] (N.Heinsius to Huygens' observations of Saturn, Vol.2, p.425).
[154] (Vol.15, pp. 240-1).
[155] (King, 1979, refers to a 123 feet telescope, p.51. Vol.15, pp.230-1).

[156] 

(Figure 4 - Saturn with the ring as observed with bad lenses and then with the moons when it was observed with good ones. Vol.1, p.486. Vol.21, p.776).

[157] (Vol.15, pp.172-7).
[158] (Vol.15, pp.246-7).
[159] (Vol.1, p.322, 332-3, 338, 382, 388, 389-392, 423-4, 457, 460-2, 463-6, 510-11, 524-5, 562-4).
[160] (Vol.15, pp.298-9).
[161] (Vol.15, p.259).
[162] (Vol.15, pp.210-352. Appendixes, pp. 353-388).
[163] (Chapelain comments of having been read by Montmor, Gassendi... Vol.1, p.483. Vol.2, pp.494-5. The telescope was 23 and 1/2 French feet long. Vol.3, pp.17-8).
[164] (Vol.1, p.396, 401-3, 481-2).
[165] (Vol.1, pp. 399-400).
[166] (Vol.1, p.412, 487-9).
[167] (Vol.1, p.431, 436-7).
[168] (Roberval to Huygens, Vol.1, p.451, 474-6).
[169] (Vol.1, p.453, Huygens' answer p.470).
[170] (Vol.3, p.373, 375).
[171] (to Chapelain, Vol.1, pp.472-4).
[172] (Bos, H.J.M., Studies on Ch. Huygens, 1980, p.150).
[173] (Vol.15, pp.214-5, 298-9, 308-9, 318-321).
[174] (Vol.21, pp.788-9).
[175] (Vol.2, p.510).
[176] (Vol.15, pp.55-92).
[177] (Vol.17, pp.351-516).
[178] (Vol.15, p.93+).
[179] (One appeared in the original edition of the Journal des Sçavans on 11th February 1669 and was reprinted in the Mémoires de l'Académie Royale des Sciences, Vol.X).
[180] (Vol.15, pp.485-6).
[181] (Vol.15, pp.316-7).
[182] (Vol.13, pp.438-9).
[183] (Vol.8, pp.492-4).
[184] (Vol.6, p.155).
[185] (Vol.15, pp.342-7).
[186] (Vol.21, pp.778-9).
[187] (Vol.21, pp.315-33).

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[188] (Vol.21, pp.334-8).
[189] (Vol.15, pp.270-1).
[190] (Vol.3, p.91, Vol.15. pp.404-472).
[191] (Turner, G.L'E, 1980, p.215).
[192] (Leeuwenhoek presented his first microscopical observations to the Royal Society and was made a member on 29th January, 1680, Vol.7, p.315. About his life and work see: Schierbeek, A, Antoni van Leeuwenhoek zijn leven en zijn werken. Lochem, 1950. Palm, L.C. & Snelders, H.A.M. edit. Studies on the life of Antoni van Leeuwenhoek, 1632-1723. Amsterdam, Roposdi, 1982).
[193]
[194] (Prop.XI, Vol.13, p.521, 684-5).
[195] (Vol.13, pp.530-1).
[196] (G.L'E. Turner, Collecting Microscopes, Milan, 1980, p.25).
[197] (Fournier, M., Huygens' Designs for a Simple Microscope. Annals of Science, 1989, 46 pp.575-596).
[198] (Vol.13, pp.512-585).
[199] (Vol.13, p.895. Vol.17, pp.287-293).
[200] (Vol.13, pp.512-697).
[201] (Vol.1, p.302, 309-311, 318).
[202] (Vol.1, p.352).
[203] (Vol.8, p.65, 92,124,125, 128-9,130-131, 204-5, 213).
[204] (Vol.13, pp.680-3).
[205] (Vol.13, p.720).
[206] (Vol.13, pp.695-7).

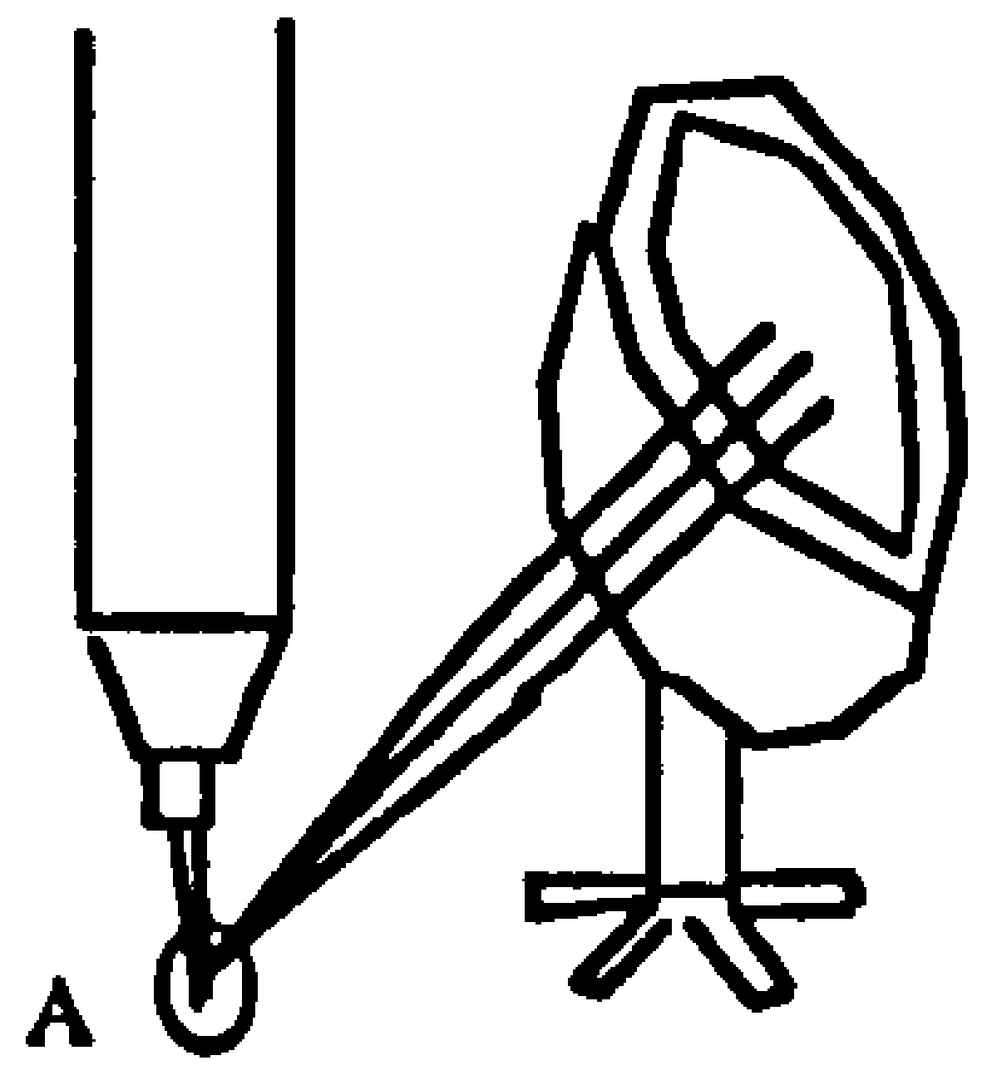
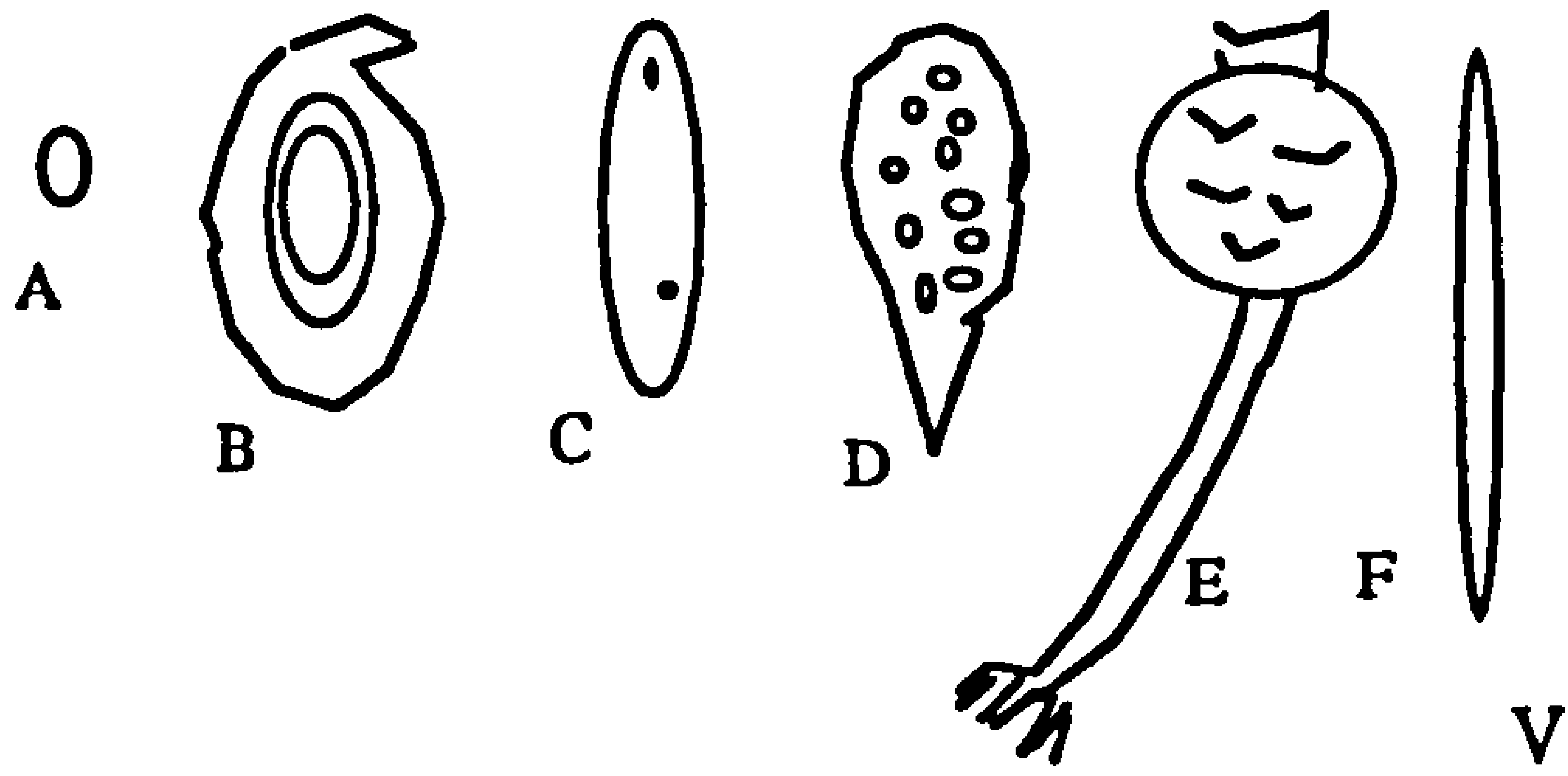


Figure 7 - Reflecting lens of 1692. A was a lens to reflect the light from the sun and from the mobile lens onto the microscope.

[207] (Vol.13, pp.686-9, 692-4).
[208] (Appendices VIII, X, Vol.13, pp.624-5, 694-7).
[209] (Vol.13, p.625, 627, 530).
[210] (Vol.7, p.400, 417).
[211] (Constantijn, father, to Oldenburg, 29th March 1675, Vol.7, pp.431-2).
[212] (Figure 8 - Observed small animals of different shapes and sizes A,B, C, D, E, F



Vol.8, p.124)

[213] (26th Dec. 1678, Leeuwenhoek to C.Huygens father, Vol.8, pp.140-1, 163, 166-7, 168-172).

[214] ("la descouverte des belles choses iroit bientot plus loin", Vol.8, pp.158-160).

[215] (Vol.9, p.310, 353-4).

[216] (Constantijn brother to Christiaan, Vol.8, p.204-6. Christiaan to his brother Constantijn "...animaux qui ne sont point venus en cette icy. C'estoient ceux qui avoient la ressemblance des Carpes, et le corps si pliable qu'ils se transfformoient en plusieurs differentes figures", Vol. 8, p.213).

[217] (Vol.13, pp.522-5).

[218] (R.Hooke, Micrographia, London, 1665).

[219] (Vol.5, p.240).

[220] (Vol.13, pp.718-730).

[221] (transparent organism: "l'objet intercepte de la lumière mais n'en émet pas", opaque organism "les points d'un objecct opaque, rayonnent eux mêmes", Vol.13, pp.522-3).

[222] (Vol.13, pp.698-719).

[223] (Vol.13, pp.720-732).

[224] (he showed its precision "*Démonstration de la justesse du niveau*" (Journal des Sçavans, 26 Feb.1680. Vol.21, p.98).

[225] (Vol.7, p.455).

[226] (Vol.21, pp.465-6).

[227] (Vol.8, pp.263-6).

[228] (Vol.21, p.83).

[229] (Vol. 21, pp.84-90).

[230] (Vol.21, pp.91-5).

[231] (Vol.21, pp.85-93).

[232] (Vol.21, pp.103-4).

[233] (Vol.21, p.97 and to his brother Constantijn, Vol.8, p.298).

[234] (Vol.10, p.410).

[235] (Vol.8, pp.377-8. Vol.21, p.133-233).

[236] (Vol.8, pp.342-393).

[237] (Vol.8, p.342. The planetarium still remains in perfect working state and has an inscription, which reads: Chr. Hugenius inventor A° 1682. Johannes van Ceulen fecit. Hagae Hollandia. Vol.8, p.343, note 5).

[238] (Vol.21, pp.133-163).

[239] (Vol.21, pp.171-188).

[240] (Pensées Meslées, Vol.21, pp.355-8).

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[241] (Vol.8, p.343).
[242] (Vol.9, pp.376-8).
[243] (Vol.21, pp.587-596).
[244] (Vol.21, pp.598-601).
[245] (Vol.21, pp.604-5 and 610-611).
[246] (Vol. 21, pp.610-647. Appendixes I, II, and III of 1694-5, pp.648-52).
[247] (This museum holds up to 30,000 historical instruments used in natural sciences at Dutch universities and also a section of some of Huygens' instruments, apart from the planetarium, and drawings of his carriages. The latter are described in a small catalogue edited by Van Gent and Van Helden, 1995, see bibliography).
[248] (Vol.7, pp.60-78).
[249] (Maps are found at the end of Vol.7).
[250] (Vol.7, pp.80-81).
[251] (Vol.22, pp.237-240).
[252] (Vol.22, pp.241-254).
[253] (Vol.22, pp.241-250).
[254] (Vol.22, pp.248-9. Divers ouvrages de Mathematique et de Physique par Messieurs de l'Academie Royale des Sciences, 1693).
[255] (Vol.7, p.359).
[256] (Great Engineers and Pioneers in Technology. Editors: Turner Roland & Goulden Steven L. Vol.1, N.Y. St. Martin's Press, 1981, p.218).
[257] (Vol.7, p.356, 357, 359).
[258] (Vol.3, p.270).
[259] (Vol.3, p.303).
[260] (R.Taton: Huygens et l'Académie des Sciences, in: HUYGENS et la France, Paris Vrin, 1981, p.60).
[261] (Great Engineers and Pioneers in Technology. Editors: Turner Roland & Goulden Steven L. Vol.1, N.Y. St. Martin's Press, 1981).
[262] (Vol.6, p.40).
[263] (Vol.5, p.28. Vol.6, pp.70-2).
[264] (Vol.4, p.180).
[265] (Vol.4, p.465).
[266] (Vol.6, p.248, 251).
[267] (Vol.5, p.29).
[268] (Vol.5, p.40).
[269] (Vol.5, p.102).
[270] (Vol.5, p.106, 116, 126, 130, 139, 354).
[271] (Vol.5, p.186).
[272] (Vol.5, p.214).
[273] (Vol.6, p.70-2, 80-1, 84-5, 124, 126).
[274] (Vol.6, p.210, 211, 224-5, 238).
[275] (Vol.5, p.363).
[276] (Vol.22, p.203).
[277] (Vol.5, p.249).
[278] (Vol.6, pp.40-1, 70-1).

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[279] (Vol.6, p.45).

[280] (Vol.6, pp.172-4).

[281] (Vol.6, p.291).

[282] (Vol.6, p.245).

[283] (Vol.6, pp. 124-5).

[284] (Vol.22, p.278. Vol.6, pp. 206-7, 211, 217).

[285] (to Carcavi, Montmor, Vol.5, p.249, 363; to his brother in law Ph. Doublet, Vol.6, pp.124-5, 173; or to his brother Lodewijk who also designed coaches, Vol.6, pp.171-2).

[286] (Vol.22, p.322).

[287] (Vol.6, pp.173-4).

[288] (to Lodewijk, Vol.6, p.169, 172).

[289] (Vol.7, p.82).

[290] (Vol.7, p.376-7, 379).

[291] (Van Gent, R.H. & Van Helden, A.C. Een vernuftig gelerde, Boerhaave, 1995, pp.26-7).

[292] (Vol.17, p.334-338).

[293] (Turner & Goulden, 1981, p.217).

[294] (Vol.2, p.473).

[295] (Vol.2, p.213).

[296] (Vol.3, p.26, 28. Vol.4, p.213).

[297] (Vol.4, p.213).

[298] (Vol. 2, p.496).

[299] (Vol.18, pp.627-9).

[300] (Vol.22, pp.278-280).

[301] (Vol.22, pp.198-9).

[302] (Bos, H.M.J. Studies on Ch.Huygens, p.158).

[303] (Vol.13, pp.438-9. Vol.15, pp.352-3).

[304] (Helden, A. van Telescopes and authority from Galileo to Cassini. Instruments. Edited by Helden, A.van and Hankins, T.L., Osiris, 1994, Vol.9, pp.7-29) .

[305] (as he called it in the Systema Saturnium, Vol.15, pp.210-211).

[306] (Hoffmann, B. Relativity and Its Roots, Scientific Ametican Books, 1983, p.50).

[307] (Oldenburg to Christiaan. Vol.7, p.417).

[308] (G.L'E Turner, Microscopical Communication, The History of Optical Instruments. Museum of the History of Science, Oxford, 1980).

[309] (Gallon. 16 Nov. 1678. Supplement, Vol.10, p.731).

CHAPTER 5

HUYGENS' PLACE AS A FOREIGN INVENTOR IN THE COURT OF LOUIS XIV

The aim of this chapter is to portray Huygens as the eminent figure he was at Louis XIV's Court. A comment is made on the politics of the time and on the origins of the Académie des Sciences before its foundation in 1666. I shall show how Huygens took an active part in the discussions and life of the Academy. Not only did he present his own work, he commented on the research produced by counterparts in other countries too. The influence of the new science -which I understand as the origins of present science- on society then and now is also considered. The figure of Huygens is emphasized as a pioneer in a new field, what later came to be: mechanical engineering.

In 1655 Christiaan Huygens was granted the title of Doctor of Laws at the University of Angers. His outstanding mathematical skills won him public acclaim and his father used to call him '*mon Archimedes*'. In 1663 he was elected a fellow of the Royal Society, and in 1665 Colbert, on behalf of Louis XIV, offered him a place as fellow of the Academy. Like other scholars, Huygens received a traditional education from a European university. However, he and his peers developed and discussed a new way of pursuing science outside the academic world. In France, the new emerging science was studied for its utility. Louis had insisted on this. Huygens, through his work, demonstrated the usefulness of technology and accompanied his inventions with mechanical theories, which opened the way to mechanical engineering.

The diplomatic career of his father had brought Huygens into contact with French circles well before his nomination as a member of the Academy. He was soon praised by contemporaries, in particular the French, for his inventions, his discoveries in astronomy, and his work in mathematics and mechanics which had come to light in the course of years of correspondence with Mersenne and Chapelain. Furthermore, he had visited France and England twice before he became an Academician, and had met French and English natural philosophers. He was also introduced to the salons, where he could be imbued with wide-reaching attitudes towards the 'new science'. When he was made a Fellow of the Royal Society in June 1663, Christiaan became officially known as a Scholar of international repute.

Huygens' work was well known before he became a Fellow of the Royal Society (1663) and a member of the Academy (1666). He arrived in Paris in 1666 to work in the court of Louis as a foreign inventor. Colbert wanted to bring together men of the highest reputation in the arts and sciences. He was convinced that an academy for the sciences would help to develop valuable projects for industrial and public use and these, in turn, would benefit the court. He particularly wanted to encourage utility in any new inventions, which were to be supported by the court. The treasury in the expectation that their application might put France ahead of its competitors funded them. With better ways of measuring longitude, it would be easier to reach the colonies overseas and to improve France's economy with commerce all over the known world. Better fighting equipment would allow them to win wars quicker, so giving France greater power. Apart from this, any invention, which would improve the welfare and pleasure of the court, was welcome. Different systems of fountains devised by Huygens and other contemporaries were applied at Versailles and in the private gardens of the influential courtiers. However, the main aims were to ensure that the new inventions were useful and to enhance the power and beauty of the Court.

In 1666 Louis XIV had only recently escaped from Mazarin's influence. Only then was he able to put into practice all his ambitions, in close collaboration with Colbert. It was the beginning of a powerful monarchy where wealth, learning, grandeur and publicity went hand in hand. This interest in science and culture permeated the court. Courtiers organized salons that soon became fashionable. These groups '*les cultes*', as they were called, met regularly and invited the learned to carry out demonstrations for them. They discussed a large variety of subjects, from philosophy and economy to the sciences. Natural philosophers, artists and writers all enjoyed a new popularity in Louis XIV's reign.

The Netherlands had become a wealthy country through shipping and its colonies and the lack of centralization at government level[1] may have not only given more freedom of thought when compared to other countries, but also may have delayed the creation of a centre for the sciences. However, the French government was more centralized with Louis and Colbert working together[2] transforming it into an administrative body. This collaboration was very fruitful[3]. After Fouquet's arrest[4] Colbert became Intendant of Finances and was nominated Controller-General in 1665[5]. Although Colbert was more successful than his predecessors in collecting the main tax, the *taille* [6] he was not liked. Colbert intended to make many reforms in agriculture but was stopped by the Dutch war[7]. He saw a good profit in industry and overseas commerce, to secure dominance in the colonies and in the ports of the New World[8]. Colbert believed that, in a state, a sound financial system should be based on attracting investment and maintaining its own[9]. It would be wrong to state that new inventions were sought at the Academy exclusively for war. After the discovery of the New World European Courts saw the economic potential of good shipping to the Americas and also to other parts of the world.

Moreover, with the advent of modern bureaucracy Huygens, together with his colleagues of the Academy, became one of the first scientists to be paid directly by the state without university attachments. He was not engaged as an academic, but because of his inventions and mathematical achievements. In a letter to Azout, Huygens said that, once in the court, he hoped to continue his skills as an inventor: *"j'espere de trouver bien moyen d'executer mes inventions quand j'en auray"*[10].

However, although efficient and diligent, over the years Colbert won general enmity in his bureaucratic role and as collector of finances. Mme de Sévigné called him the 'North'. Towards the end of his life people did not like him. In order to bury him in peace, they buried him at night. His death coincided with a turning point in French politics. The war with the Dutch had emptied the treasury's coffers and the economy was weak. Cuts were felt in those institutions without political weight. The Academy was one of them, and no foreign members were appointed after Colbert's death. Huygens remained in The Netherlands after 1682.

1. ORIGINS AND PURPOSE OF THE *ACADEMIE DES SCIENCES*. HUYGENS' APPOINTMENT AND HIS WORK IN FRANCE.

Colbert created various specialized centres before and after the opening of the Academy. It could have been an influence of the spectacular results obtained with experimental science and the new scientific instruments. In 1662, he opened the Royal Manufactory of the Gobelins. The Academy of Inscriptions closely followed it, in 1663[11]. In 1665 the Journal des Sçavans started its publications, preceding the Academy of Sciences of 1666 and the Observatory in 1667. The letters patent for rare plants were made official at the Royal Botanical Garden in 1673. Each institution had their rules and members abode by them.

Colbert loved his work and anything that would enhance the figure of his king. He protected the arts and sciences because he believed that they should flourish under a great monarchy. Nevertheless, Chapelain and Colbert took steps to avoid any criticism of the king. Historians were not allowed to see very important archives, which would have given them the chance to discuss highly sensitive issues. Historians in exile were more objective, for example, the Huguenot Michel Levasser criticized Louis XIV in his ten volumes of history published in Amsterdam between 1700 and 1711[12]. It was not until 1713 that Father Daniel wrote an erudite history of France[13]. Colbert was crucial in the promotion of the Sciences and the Arts at Court. They flourished while Colbert held office, and his liberal administration of the newly founded academies gave their members the chance to develop new ideas.

There was a great interest in the new development in science, in particular, after seeing the spectacular results obtained with experimental science and the new scientific instruments. Science became very popular amongst the French court, the bureaucrats and other social circles. At the time when the different Academies were working regularly, the cultes created their own gatherings where they invited scholars from the sciences and the arts. They favored what they knew best, the arts. The 'literary' salons began with Louis XIII[14]. Under Louis XIV, they also discussed issues of natural philosophy. In 1661 Huygens mentioned them in his Journal de Voyage[15]. He saw Rouhault demonstrating the 'new science' to the public[16]. Huygens found supporters on the debate on Saturn[17]; this increased the interest of the public for new science and made the Dutch experimenter known amongst French circles.

Molière described the salons in his plays. In the Femmes Savants, played in the court in 1672, he exaggerated their enthusiasm for the use of perfect language and speech, as a necessity for belonging to these elitist groups: "Belise: "Ton esprit, je l'avoue, est bien matériel. Je n'est qu'un singulier, avons est pluriel. Veux-tu toute ta vie offenser la grammaire?". Martine: "Qui parle d'offenser grand'mère ni grand-père?" ... Belise: "Grammaire est prise à contresens par toi, et je t'ai déjà dit d'où vient ce mot". Martine: "Ma foi, qu'il vienne de Chaillot, d'Auteuil ou de Pontoise, cela ne me fait rien". Belise: "Quelle âme villageoise! La grammaire, du verbe et du nominatif, comme de l'adjectif avec le substantif, nous enseigne les lois". Martine: "j'ai, madame, à vous dire que je ne connais point ces gens-là". Philaminte: "Quel martyre!". Belise: "Ce sont les noms des mots, et l'on doit regarder en quoi c'est qu'il les faut faire ensemble accorder". Martine: "Qu'ils s'accordent entre eux, ou se gourment, qu'importe?"[18].

In the same way discussions of classics and the new science must have been common. Experimental science had brought about difficult concepts such as subtle matter: Trisottin: "Je m'attache, pour l'ordre, au péripatétisme". Philaminte: "Pour les abstractions j'aime le platonism". Armande: "Épicure me plaît, et ses dogmes sont forts". Bélise: "Je m'accommode assez, pour moi, des petits corps; mais le vide (vacuum) à souffrir me semble difficile, et je goûte bien mieux la matière subtile". Trissotin: "Descartes, pour l'aimant, donne fort dans mon sens". Armande: "J'aime ses tourbillons". Philaminte: "Moi, ses mondes tombants". Molière went further and ridiculed those societies where the cultes talked about these matters simply because it was considered fashionable since the Academies had made the new ideas and discoveries available to the public. However, it shows that they were aware of the new discoveries: Trissotin: "On en attend beaucoup de vos vives clartés, et pour nous la nature a peu d'obscurités". Philaminte: "Pour moi, sans me flatter, j'en ai déjà fait une, et j'ai vu clairement des hommes dans la lune". Bélise: "Je n'ai point encor vu d'hommes, comme je crois; mais j'ai vu des clochers tout comme je vous vois"[19]. This shows that there were amateurs using astronomical instruments. Examples of their interest in scientific issues are found in Huygens' correspondence: Le Duc de Roamais suggested to Huygens the use of the spring instead of the pendulum[20].

It could be said that this impact on society at the time was due to this open discussion of the 'new science'; and the associated publications made it more accessible to the laymen than ever before. It was developed outside the universities, and the new empirical sciences benefited from direct public participation in the confirmation of observations. Scientific laboratories, of course, did not yet exist as a place for professional experimentation. Ideas and experiments were instead discussed at the academies of science. There were, however, private laboratories, such as Boyle's in England. Huygens already had his own workshop in The Netherlands for lens-grinding and for building his own models of various instruments. And, although he did not refer to it in his correspondence, Huygens must have had a laboratory in Paris to carry out experiments on the air-pump when he worked with Papin, because the latter was not a member of the Academy. The experiments must have been performed in his workshop and then shown to the Academy. The natural philosophers had to present their discoveries to the scientific world and to their sponsors to convince them of their use and importance.

Around 1663, Huygens received a series of general rules of what an Academy for the sciences should be[21]. Soon after, Huygens took an active part in designing rules for it. He sent some suggestions in a letter to Chapelain: the Academy should discuss natural philosophy[22]. Since Mersenne and Montmor's academies had worked so well, it was not difficult to convince Colbert to take up this idea. Chapelain talked to Colbert about Huygens as early as 1663[23]. Colbert then commissioned one of the "*Premiers commis*", Dumetz, to add Huygens to the list of pensions given by the king as a present. Chapelain wrote to the Dutch scholar about thanking the king for this present, but suggesting that first of all, he should thank Colbert because he had been the real originator of all this[24]. Chapelain was well aware of the minister's power.

In 1664 Huygens traveled to Paris and England again. He joined in French social life once more. He attended Molière's Le Mariage Forcè and the ballet, music recitals and a dance where the king was present[25]. Huygens received his pension on his way back from England. Beneficiaries of the King's pensions had to report to Colbert[26]. Huygens arrived in Paris from London on October 1663 and received a pension of 1,200 French pounds. However, this was not much compared with what poets and *romancers* received. Oldenburg commented to Boyle on how much more was given to the arts than to sciences[27]. The most substantial benefits were given to foreigners to attract them to France.

In the list of beneficiaries Huygens was called a 'great mathematician and inventor of the pendulum clock'[28]. In June 1665, Huygens was officially invited by Colbert to become a member of the planned Académie des Sciences, founded in 1666. However, he did not know how much the pension would be yet[29]. He was made a Fellow member of the Académie des Sciences in 1666 and awarded 6,000 French pounds a year; Cassini, the Italian astronomer, received 9,000. On the other hand, the Arts was what they knew best and the new science still had to prove itself worth the risk of being sponsored. Furthermore, the scientific activities of the Academy were for the profit of the Court, whereas the Arts provided the propaganda. The work of the natural philosophers was too new to be understood by the majority. I agree with Ornstein that the Academy had adequate resources, since the king was the protector and the royal treasury provided the funding[30]. Colbert spent 88,000 French francs annually at the Academy, of which 51,000 were destined for practical and technical projects[31]. As Stroup has recognized, engaging foreign members would increase publicity about the king in those countries[32].

In the seventeenth century, society and the state influenced the development of science. European courts offered prizes for inventions and solutions to problems. These awards provided not only monetary reward, but also fame and recognition. Much of the advancement of science was very much due to the interests of these courts, obviously to gain prestige and power. Ferdinand II, Grand Duke of Tuscany, organized the first network for meteorological observations: pressure, temperature, humidity, wind direction and the state of the sky. He arranged for these observations to take place in Florence, Pisa, Vallombrosa, Curtigliano, Bologna, Parma and Milan. The same was organized later in Paris, Warsaw and other European cities. The Grand Duke found that the column of mercury descended six units in the scale used when it rained[33].

Chapelain was an effective go-between connecting the French circles with Huygens and his work. They knew of his experiments with the air-pump as well as those with the pendulum clock and that had made him an internationally acclaimed inventor. Colbert organized the funding of the Academy through the Royal Treasury[34]. Engineers were called from abroad to work on chemical work and engineering[35]. Of special importance here is the fact that with Huygens the concept of engineering changed completely to mean mechanical engineering. He pioneered a new field in engineering. He was able to advance in this field because he distanced himself from philosophy when explaining basic mechanical principles by geometrical theory. He was known as an inventor and, unlike his contemporaries, he created the tradition of explaining automata in mathematical terms.

Colbert invited suggestions and ideas for future research from the natural scientists selected to become members of the Academy. He clearly wanted to know what these learned men could present as innovative and interesting. Huygens gave several suggestions for experiments with the air-pump, with the forces of gunpowder, steam, air and concerning the impact of bodies; Colbert ticked those that were of interest to the court[36]. Under Colbert the Academy, amply funded, produced notable results. Huygens became one of the first foreign natural philosophers to be paid a regular pension in a very bureaucratized Court. This provided security and a certain status, difficult to obtain in any profession except for those who held office, namely, academicians at universities.

1.1. Origins of the *Académie des Sciences.*

The 'new science' originated outside universities in the seventeenth century, but why? The publications of new philosophies: Bacon, Descartes, Gassendi and the translations of Greek texts were available all over Europe from the 1640s. There was also an important Baconian influence upon natural experimenters, who showed the need for experimentation and for collecting the maximum data possible from nature. This, combined with the invention of experimental instruments, fuelled the development of the 'new science' within groups of scholars who did not conform to academic curricula. Men with power, from the king to bureaucrats and diplomats, as well as Dutch merchants supported them and the English aristocracy, saw in the new inventions a profitable business. These could be applied to industry and thus increase their wealth and power over other nations. This encouraged an interest in science in the Orange family. In France, Colbert decided to create an official centre, which would work for the profit of the court: the Académie des Sciences based on the success of Mersenne's gatherings.

Mersenne was the organizer of the first group of scientists who set the example for the creation of two important centres for the development of the 'new science': the Royal Society in London and the Académie des Sciences in Paris. In 1635 Mersenne suggested the creation of an association whose members would correspond regularly[37] with other scholars all over Europe and between themselves. After his death and from 1648 until 1654, Le Pailleur, a learned man, kept the meetings going. Montmor took over from 1654 until 1664. He was interested in clocks, mechanics, and medicine. He became a protector of the group of natural philosophers and doctors of medicine. However, the meetings were more general and open to the public. Finally, the traveler Thévenot kept this group going from 1664 until the foundation of the Academy. In his journal of 1661, Huygens commented about meetings at Montmor's. Non-scholars also gave seminars on the new developments of science[38].

The Intendant of Finances made these gatherings official when he opened the Academy in December 1666. It was based at the Bibliothèque du Roi, in the Louvre. The main aim Colbert had in mind was to advance the sciences. For that purpose he selected the best known mathematicians and doctors of France and from abroad; Huygens and Cassini were invited to join. They had been in the original group of natural experimenters and kept in touch through regular correspondence. All these were rules drawn up when the Academy was founded[39]. The debates were between scholars and focused on specialized subjects. They were not as general as those held at Montmor's.

Although Plantefol states that the aims of the Academy were to present the most useful projects and to discuss them[40], I believe it was more complicated than this. There were also projects based on experimental science, such as those made with the air-pump. Unlike Plantefol, I would not call the Academy the official centre for scientific research in France, but rather one of the two European centres that contributed to the creation of the new science. The laws of nature could be explained in terms of basic physical laws and showed the application of technology for everyday use.

As McKie states, the members gained reputation by belonging to the Academy and they were able to choose specific problems for study and research[41]. It could be added that they became internationally known and acclaimed because they shared their work with other European experimental researchers through their correspondence. Huygens was a good example of this. However, the founders of the Academy "had explicitly rejected doctrinal dogmatism as contrary to the progress of science"[42]. This can be seen in the variety of opinions they gave on each subject, yet they were still published in the Journal.

1.2. Huygens and his scientific work in France.

Huygens' trip of 1661 brought him into contact with two very different groups: the scientific meetings at Montmor's and the social gatherings of les cultes. The variety of subjects discussed must have impressed Huygens. I believe that they inspired the young Christiaan to work in more fields of knowledge when he went back to The Hague. During this trip he attended meetings on what was considered the latest developments in natural philosophy[43].

Foreign scholars and experimenters thought it a privilege to be invited to work for the most powerful king of Europe at the time and this included Huygens, who admired his liberal thinking "*graces de sa felicitation, et de ses soins a fair continuer la liberalitè Royale*"[44]. The French court was seen by the foreign inventor, Huygens, as a modern and dynamic one where those invited to work for it would enjoy freedom of action: "*assurances qu'on me donne que j'auray toute sorte de satisfaction*"[45].

He was highly admired by the learned circles of the time. It is not surprising that he would be invited to the Academy after ten years of scientific achievements and inventions that he had already shared with all other academies from Mersenne's to Montmor's. In 1663 Huygens was asked to give his opinion on a draft of the possible rules for the Academy. One of them stated that the invention of *nouvelles machines* (new machines) was essential to fulfill the main aim of the Academy: to perfect the Sciences and the Arts, and to find what would be of utility or comfort (*commodité*) to all, in particular, to France. The new inventions, machines and discoveries would be made public for the benefit of the many and should be applied to public and private works. The utility of the design would be studied before the machine was made[46]. Soon afterwards, Huygens received a very enthusiastic communication from Moray and the new Society they were creating in London[47]. In 1665 Huygens was invited to join the new Academy. This is not surprising since he fulfilled all the requirements set by this centre. Furthermore, he was well known to Colbert and all the French scholars and to Louis XIV who had given Huygens a 'privilege' or patent for the invention of marine clocks[48].

To talk about contemporaries in the social context in which Huygens worked means to study the learned men who were not attached to universities. From those meetings, discussions, studies, works and correspondence, the new modern science developed. Instead of natural philosophers Hooke called them: "experimental searchers"[49]. It is curious to note that in the entire correspondence Huygens hardly referred to the academics at the universities. Science developed quickly outside their restricted enclosure. A free atmosphere was required for the new ideas which emerged from all the work and seminars of members with different backgrounds, gathered together under the scientific organizations of the time. They were able to pursue their own scientific interests. In England, some experimenters had a good income to support themselves and their research. This was true of Boyle. Others were employed by the Royal Society, such as Hooke, who became one of the first English paid technicians; they were 'operators' outside the universities. The scientific meetings in London took place first at Gresham College, then at the Royal Society. Already in 1654 John Webster had demanded a Baconian learning from universities, rather than the Aristotelian approach used[50], but this did not happen until the Royal Society and the Academy showed the impact of new ideas and the need for progress.

Academicians discussed each other's work at the regular meetings. There were two meetings a week and the proceedings were recorded. They presented their work, and those present raised questions. They also suggested changes to other members' inventions and to the work of foreign counterparts. Huygens, for instance, discussed Thevenot's level[51] and in another meeting he talked about Newton's catroptic lens[52]. De La Hire suggested collaboration between Huygens and other members to develop a theory of gravity[53]. The ambience of the Academy was such that, rather than competing against each other, they were able to cooperate in projects together and also presented their own work. Although somewhat disorganized and maybe incomplete, records of their work appear in the Mémoires de la l'Académie. The subjects covered a whole range from geometry, mathematics, astronomy, and physical machines for experimentation, such as the air-pump, to medicine. Huygens' studies appear in volume X. In 1668 he presented a book in geometry[54]. In 1669 he discussed his observations on Saturn and the demonstrations relating to the impact of bodies on which he had worked jointly with Picard. In 1672, he discussed Newton's catoptric lens and gave a full account of his own air-pump accompanied by a drawing of it, as well as further observations of Saturn and a newly invented two-liquids barometer, with an explanation of how to measure pressure with it. In 1675 he presented an extract of the new portable clocks he had recently designed and in 1680, he explained the new level built with two or four convex lenses[55]. This shows the extent of Huygens' activity. He demonstrated his own designs and theories and discussed the work of other members of the Academy and of scientists from abroad. He was up to date with the latest research.

I agree with Stroup[56] that it is difficult to elucidate the way academicians fitted into the social and economic structures of the Parisian court. It is important to take into consideration why they had been given a position in the court. They worked on a fixed salary, which provided them with a certain status, almost similar to those holding office. Furthermore, their voice was heard. They did not receive commissions to do specific work, as painters did. On the contrary, they could set up their own research and submitted it for final approval to the bureaucrats. In the Academy they worked as a new and independent group, whose ideas were not only respected and admired abroad; but also paid for their research. They developed new methods and theories and with them several fields of science. Other experimenters in Europe used their work. The international contacts promoted by the centres for science were fundamental for this recognition and for the dissemination of new ideas in England and France. Both societies, the Academy and the Royal Society, worked as intellectual catalysts from which many scientists in Europe benefited, as did the new way of 'making' science.

By contrast, in the Low Countries there was no scientific body to gather together those who sympathized with the emerging new science. Instead, individuals worked on their own but corresponded regularly with other scholars. Apart from Huygens, we find amongst others: Beeckmann, van Helmont and Leeuwenhoek. The government, less centralized, was mainly run by a free merchant economy and its representatives were freely chosen. This allowed for a certain amount of independence. It was easier for new ideas to be published without restrictions. In 1649, Schooten edited in Latin Descartes' Geometria. Although the political climate was quite liberal compared to other European countries, the universities were, in general, reluctant to change traditional training methods and to include Descartes in their curricula. There were tutors such as Von Schooten who taught Cartesian philosophy in their classes, in Leyden, but not without inciting discussions in the Theology faculty. Catholics saw the new philosophy as a threat. Their pressure made the state pass a resolution forbidding the teaching of Cartesianism in 1656. Although faced with opposition, especially at Leyden, and from the theologians, the new theories spread within the universities. Cartesianism and the revival of atomism were a threat to traditional philosophy and to the foundations. How much faith the respective Courts of the time had in the traditional universities may well be questioned. Louis, for instance, gave his patronage to experts from outside universities.

The new Cartesian philosophy created a division between the followers of the Ancients and the Moderns, who preferred Cartesianism, or those who learned from both. For instance, de la Granje published a book on several authors that included atomists, Gassendi and Descartes[57]. Moreover, there was another current of thought at universities which remained Thomist and, therefore, Aristotelian. The 'new science' confronted it. An example of such differences appears in Fontenelle's Disgression sur les Anciens et les Moderns, 1688, and in Perrault's Parallèle des Anciens et des Moderns, 1688. Rohault could be included in the first group. In his Traité de physique (Paris, 1676) he referred to Greek philosophers and contemporaries. Discussions between philosophers and theologians were brought about at *La Sorbonne* and between Cartesians and atomists. Rohault wrote Entretiens sur la philolosophie (Paris, 1671) to defend himself against these theologians because they wanted to censure his philosophy. However, his works became textbooks at the university in the 1670s. They were also translated into English in the eighteenth century[58].

It was experimental researchers such as Huygens who were able to apply the best of both: the modern philosophies of Bacon and Descartes, and the atomism of Gassendi and the Atomists. This is widely found in his correspondence. (I call modern science the development of Cartesianism and Baconianism in the 17th century and new science the work which pioneered new fields of science, such as mechanical engineering in the case of Huygens). Unlike Ornstein (1913), I do not believe that the Academy tried to propagate Cartesian views and principles. Historians have used this statement glibly. Huygens criticized Descartes' work and proved his laws of impact wrong. Furthermore, he drew his 'theoretical mechanics' with a geometrical and empirical basis for any instruments he designed. It was the beginning of a new age and field in mechanics: mechanical engineering.

Huygens maintained correspondence with non-academic learned men of the time. He exchanged information with contemporaries through intermediaries: in England, first through Moray and then Oldenburg whom he met in 1661, maintaining good relations with the Royal Society[59]. In France, first with Cl. Mylon who made Huygens' work known to French circles between 1656 and 57[60] and later, from 1658 onwards with Chapelain[61], who let Huygens know what the French natural philosophers were working on[62]. In 1659 Chapelain sent him a copy of Roberval's clock and received a copy of the Systema Saturnium from Huygens. He wanted Chapelain to let everybody know that the clock was available for sale and that anybody could order it[63]. However, he did not yet want to disclose how it was built[64]. Maybe because he still had to publish the accompanying treatise. French bureaucrats therefore, knew Huygens' work as early as 1656. For instance, Boilleau was secretary to Jacques Auguste de Thou, the French Ambassador to the Low Countries in 1656, and received, through Mylon, Huygens' lenses[65]. With them, Boilleau was able to observe Saturn whereas he could not do that with his own.

Natural philosophers also influenced each other's work. Huygens was an important example of this. He influenced contemporaries, such as Leibniz, who recognized so in his letters[66] and Newton. However, some historians still deny this[67]. Huygens also met philosophers and knew about their work. He was interested in Locke's philosophy, especially after meeting the author and Newton in England in 1689[68]. Locke wrote in his treatise about the nature and value of ideas, and with an idea of space different from that of body[69]. Huygens was looking for other explanations of space, simply physical. Was he trying to understand relative space? Academicians had to be in contact with the other French Academies too. It was stated so in a draft of 1663 of the rules of the Academy[70]. For instance, Racine was received at the Academy in 1673[71]. Whereas Pellison, who was writing the history of Louis XIV, received information from Huygens about the experiments on the air-pump and comments on how innovative they were[72]. Although unrecorded, it must have been common to visit other academies or to know about their work.

Huygens' popularity grew outside learned circles as his correspondence with amateurs and other folk show; with them he discussed some of his work. He helped to popularize science theoretically and experimentally with the instruments he invented. His explanations of the use of his instruments were intended for all that might be interested. This can be seen in his telescope and the air-pump. For instance, Huygens demonstrated how the pendulum clock and the air-pump worked to a member of the gentry on his visit to London of 1663[73]. In January 1665 he said he was receiving thousands of letters from persons, known and unknown. The queries were mainly about his observations of the moons of Saturn: "*j'ay en une infinitè de lettres a escrire, a des personnes connues et inconnues*" and "*une communiquant leurs observations et demandant les mienes*"[74]. However, the original letters have not been found. The main interest seems to have been in astronomy. Correspondents asked Huygens for advice; they seemed to have acquired their own telescopes. This shows that the new science was indeed permeating society, in general, and not only the higher classes.

Huygens complained about those contemporaries who tried to destroy his work. In 1690 he called Mariotte a plagiarist because in his treatise on the impact of bodies, he had written propositions identical to those of Huygens stating that they were contrary to Descartes, without giving Huygens any credit[75]. At the end of his life, he described Hooke as having a suspicious mind and becoming very easily upset[76]. Christiaan's father, defended 'his Archimedes', in his letters to Oldenburg against Hooke. When in 1675, Hooke was claiming priority over a circular clock, Constantijn insisted that "*mon Archimedes*" had already discovered it in 1658[77]. On the other hand, the controversy with Abbé Catelan lasted years, and in his correspondence Huygens patiently tried to explain what Catelan had misunderstood. However, Catelan continued his criticisms on different aspects of Huygens' work especially concerning the axioms of the pendulum clock. It went on until the 1680s[78].

Huygens also realized his limitations when some scientific problems were put to him. Differential calculus developed by Leibniz and Newton was not as easy as his geometry. He was more successful in his studies on geometry[79] and in his inventions. Nevertheless, Huygens saw the usefulness of calculus, as he commented to contemporaries[80]. He worked less on subjects where he could not produce a complete explanation or a whole treatise on the subject.

Louis, unwittingly, had supported the independent development of new scientific research and, consequently, of new fields of science. This would not have been possible in the controlled and closed regime of the universities. Huygens, for example, was a pioneer in the field of mechanical engineering. He was able to dedicate his time to research and complete the writing of the Horologium Oscillatorium of 1673, which he dedicated to Louis XIV. The king had recognized how useful the clock would be for the state and the public, and fostered in his Court the most advanced sciences and inventions[81]. The king had several clocks made by Huygens in his own palace[82]. The French-Dutch war of 1672 did not seem to stop Huygens from praising the very king who was at war with his country of origin. In July, William of Orange became Stadholder. By then the Spanish army was allied with the Dutch against the French[83]. Racine in his Eloge historique de Louis XIV explained the motives for this war as a means to put the Dutch in their place[84]. Sonnino attributes its outbreak to a common wish in both countries[85]. Another reason for the war may have been the wish of Louis to achieve still greater political and religious power throughout Europe. Later on, in 1685, Louis revoked the Edict of Nantes[86], determined to root out Protestantism, more than 175,000 Huguenots found refuge in various countries[87]. Some provinces suffered economic depression[88] because of the departure of so many professionals[89]. Religious toleration was used to increase the hate against Catholic oppression[90]. Some of them were clockmakers who ended up in The Netherlands and influenced Dutch clockmaking. The Huguenots seemed to have been used to strengthen Louis' new vision of a united France in land and religion. This would support Ashcraft's comments on the use of groups of society to strengthen a political theory[91]. A more pluralistic approach to history is necessary[92].

The Horologium Oscillatorium represents the full description of an instrument of precision, the clock. With this treatise, anybody could understand how the clock worked and how to develop more complicated instruments using its basic principles. The instrument was reproducible and the theory could be understood with geometry.

Had Huygens been at a traditional university, he would not have had the time to write such a treatise. First he would have dedicated a lot of time to teaching. Even more important was the fact that the system of learning was based on a totally different method and on principles still totally rooted in the old tradition. However, Huygens' work in general and the Horologium Oscillatorium in particular, showed a creative mind capable of carrying out independent and learned research in many fields of knowledge. In the same way that Newtonianism in England spread from the scientific societies to the universities[93], the French scientific research of the Academy influenced traditional universities.

Stroup recognizes that the Academy's interest in technology is reflected in the studies of "machinery, which date back to Colbert's protectorship. Throughout the century academicians and their paid associates designed and tested apparatus and outsiders also submitted inventions to the group, hoping for its approval"[94]. Huygens was a key figure, in my opinion, for those inventions that pioneered the use of patents and the utility of technology for everyday life. After that, a new tradition of inventors emerged in 1680s France. They did not have to graduate at a university, nor did they have to be a member of the Academy, only associates. They simply invented apparatus that they expected would be approved and bought by the state. A system of patents followed. This began at the Academy. In 1668 Huygens and other Academicians, together with the secretary of the Assembly, listened to Reusner who claimed to have the invention for the measure of longitude. It consisted of two machines. The audience concluded that the method was complicated and that longitude could not really be assessed[95].

As far as social life is concerned, in his first year at the Academy, Huygens commented in his correspondence that he had attended a ballet in Paris. The company had been a few weeks in Saint-Germain where the Court used to spend most of its time[96]. I believe that socializing between the gentry and the groups of *cultes* must have been quite normal and not something that would be referred to in the correspondence. For instance, in 1661 Christiaan said that he had gone riding with Le Duc de Roamais[97]. In 1677 Colbert gave a party to all the members of the Academy in his Château de Sceaux[98]. There is very little material available from which a more complete idea can be drawn of academicians' life outside the Academy. Unless a diary is found, or letters with a reference to their social life, it is not something we shall ever know. Huygens was also very interested in the political and social affairs of the time as can be seen in his letters.

In his correspondence about the state in affairs of other countries of Europe, he was concerned about the use of his own work on gunpowder for other than useful purposes. Huygens received news from his brother about the defeat of the Spaniards in battle with the Portuguese, and Christiaan attributed their victory to the use of cannon[99]. This may have driven Huygens to question the ethics of using gunpowder for war. Natural researchers at the Academy discussed the distance traveled by a cannon ball in order to improve its military possibilities. This was another use of their work as far as Colbert's aims were concerned. Huygens also wrote about this subject and experimented with gunpowder in the vacuum. However, he questioned the ethics of using gunpowder for cannon.

Huygens was aware of the diplomatic problems between France and The Netherlands. The Dutch were in the process of restoring the House of Orange. His father Constantijn was an ambassador in this difficult environment[100]. Some historians may think that the Dutch did not like Christiaan Huygens because he was still at the Court of Louis XIV while there was a war between France and The Netherlands. But there was a strong pro-French feeling and, until the House of Orange was restored in 1672 with William III, those in charge of affairs and politics were very pro-French. William III was against Louis in politics, not necessarily against the learned scholars he had engaged to work for him in Paris. His government was not a democracy, but an oligarchy and public affairs were silenced[101]. The two parties, the pro- and the anti-Orangists, kept criticizing each other in order to win popularity.

The flow of Huguenots after 1685 must have created again a more pro-French attitude and also Christiaan had not returned to France after 1682. Pro-French people may have been less liked in this changing atmosphere and the Huygens family belonged to this group. However, Christiaan could not be categorized, he was not involved with politics, or diplomacy, as his father and brother were. His work was mainly scientific. I agree with Struik that the French-Dutch war of 1672[102] did not affect Huygens' position, or his reputation amongst the scholars of the time[103]. As Treasure says, Huygens considered himself a citizen of the world, where he had the mission of promoting science[104]. Furthermore, the wars fought were about trade and dominance at sea and they did not disturb the world of learning.

The Royal Society, however, continued in a similar tone since its foundation. This could be because it did not have the support of a king[105], because Charles II had his own group of Scholars at court[106] and survived because some members financed their own research, e.g. Boyle.

When Colbert died Huygens' popularity diminished, as did that of his colleagues from the Academy. He remained in The Netherlands after his last trip in 1682 until his death in June 1695. The fact that he was not called back after 1682 he attributed to jealousy[107] since he had no personal differences with anybody there[108].

1.3. Impact of the New Science on Traditional Philosophy. The Development of "New Science", its uses and misuses.

In the <u>Assayer</u> of 1623, Galileo said that in order to understand the book of the universe, it was necessary to know the language in which it was written: mathematics. Galileo's influence on the new emerging science has been amply demonstrated; as well as Bacon's in natural philosophers, However, they did not show the applicability of geometry as a basis for explaining technology, and it is in this that Huygens' originality lies. With Drake[109], I agree that Bacon, Galileo and Descartes knew that the Aristotelian tradition had to be changed but not, as he says, because it was a bad tradition, but because the Baconian idea of accumulation of data was important for the development of the "new science". Sarton for instance disregards the impact of Huygens' work and mentions only Newton after Descartes[110].

Descartes' philosophy was indeed influential in the new science in that it showed a novel way of questioning how the natural world worked. Huygens understood this message and used it to create a framework for a new methodology in science. Huygens' work in mechanics, in particular the Horologium Oscillatorium, seem to have pioneered the field of mechanical engineering by the use of Archimedean geometry to prove 'per se', in a logical deductive method a mechanical instrument. The pendulum clock does not represent events from the natural world. However, it is an instrument with which those events can be studied under precise periods of time.

It was different for the air-pump. This was a physical instrument used by natural philosophers to represent what was happening in the natural world and so explain it better. However, Huygens realized his limitations when he also tried to develop an underlying theory of statics and dynamics to explain the physical phenomena observed with this instrument. Instead he developed a theory of matter with the new ideas suggested by previous systems of philosophy, those of Galileo, Descartes, Gassendi and, in particular, Democritus. The air-pump was crucial to natural philosophers such as Boyle and Hooke because they followed the Baconian tradition of accumulating data from observations.

These, in turn would prove hypotheses upon which the new science could lay its foundations. Instead of an "accumulation of correct data ...from which new improved theories were derived"[111], it could be said that science developed according to new hypotheses, which were proven right or wrong through experimentation. The data obtained can always be improved; therefore, it should not be qualified as correct, but stated simply as data. It is from a collection of proven hypotheses that a new theory derives.

Rohault introduced the new physics and the theoretical basis that accompanied machines into the universities. He worked in the field of physics and dropped the metaphysical basis of Cartesianism[112]. His books were the first to be used at universities as textbooks. The treatise of 1671 was published several times, and the books of 1675 and 1676 were published with experiments and designs of simple machines, because of the influence of the Horologium of 1658 and the Horologium Oscillatorium of 1673.

From the 1660s instruments became popular[113] and were sold in the market place. Different people used them: from amateurs, wealthy gentry or merchants, to other experimental researchers who wanted to learn about other fields of study.

The new science developed rapidly from the 1650s to the 1680s. Huygens joined the stream of new developments in science, where he played a key role in the development of a new field of engineering with the creation of an instrument of precision, the pendulum clock. The accompanying treatise explained, for the first time, how a specific device worked and the basis of its construction with a geometrical theory. Books on mechanics, especially, in engineering, followed this pattern from then on. He broke away from metaphysics and this enabled Newton to follow a specific format for his own work in mechanics. This was not the aim of natural philosophers. They focused their efforts in explaining natural phenomena rather than creating simple mechanical theories to explain how an instrument and its parts worked.

The new science kept evolving from then on because of the basic principles it was based on and its applicability[114]. Both mechanics and physics evolved into specialized fields of knowledge.

Scientific instruments proved to have different uses. Instruments of precision were essential in mechanical studies, and physical instruments in physics. In the 18th century they had become standard for demonstrations at universities. Two things seem to be clear as to how the science of the seventeenth century influenced society and changed the scientific method. Hypotheses could be proved with the help of instruments. The performance of the experimental apparatus could be seen and the results compared, discussed and recorded for further reference. On the other hand, the new discoveries of science were used, not only for the good of the society, but also to gain power. More powerful weapons were eventually developed. More destruction was possible with more efficient weaponry. But also commerce was increased with better shipping.

Huygens thought of himself as an inventor. In his correspondence he referred to "his inventions" and the "machines and automata" he was working on[115]. Therefore, it can be concluded that Huygens was appointed a member of the Academy because he was an inventor well known in scientific circles through his regular correspondence with *sávants* throughout Europe. By then he had exchanged information about his theories and solutions to mathematical problems, and about his instruments and how they worked. It makes sense to infer that the usefulness of his inventions was his best asset, since the Academy had very good mathematicians. Therefore, he would not have been called as a mathematician, or as an astronomer, because that was Cassini's role. Nor was he appointed as a physicist because theoretical physics had not been developed yet. He was instead made a member because of the utility of his inventions, and this was an important aim of the Academy. Just as Baconianism was developed by Restoration scientists[116]. The image he had drawn of himself was that of a potential inventor who would create useful designs to improve different crafts. Colbert was especially interested in this. Huygens was emerging as a pioneer in the field of mechanical engineering, applying his own method. To this only a few variations had to be introduced to make the basic design applicable to different crafts.

Already Huygens criticized the misuse of the "new science" for weaponry in the seventeenth century. A more practical way of thinking developed one of utility and profit as well as the pursuit of power and dominance. Towards the end of the seventeenth century the general belief was that with science it was possible to develop inventions of great use to society[117]. How quickly did this new science filter through to society[118] and appeared in contemporary popular books and literature? The best sample is found in Diderot's works where science was defined as the study of what could be demonstrated and verified by experiment, and syllogisms and conclusions could all be drawn from nature[119]. In his Pensées sur l'interpretation de la nature (1754), Diderot recognized the "new science" working in all fields of knowledge well established by the mid-eighteenth century and accessible to all[120] and how the Newtonian system had influenced it[121]. Huygens' works were quoted in the eighteenth (Laplace, D'Alembert) and nineteenth centuries (E.Mach)[122].

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[1] (Schama, S. The Embarrassment of Riches, 1988. Hackmann, W. The Growth of Science in the Netherlands, in Crosland ed. The Emergence of Science in Western Europe, Macmillan, 1975, pp.89-109).

[2] (Jean Baptiste Colbert (1619-1683), Marquis de Seignelay, succeeded Mazarin as minister to Louis XIV; Bluche, 1990, p.126).

[3] (It was Colbert who drew the naval ordinances of 1669 and the shipping ordinances of 1689, which were first approved and signed by the King, finally, by Colbert. Bluche, 1990, pp.135-6).

[4] (Stoye, J. Europe Unfolding. Fontana Press, 1988, p.195).

[5] (Bluche, F. Louis XIV, 1990, p.329, and, also by Bluche, Louis XIV vous parle, 1989).

[6] (Beik, W. Absolutism and Society in XVIIth Century France, 1985).

[7] (Bluche, 1990, p.332).

[8] (Ashley, M. A History of Europe 1648-1815. Prentice-Hall, New Jersey, 1973, p.70).

[9] (Munck, 1990, p. 347).

[10] (to Azout, September 1665, Vol.5, p.483).

[11] (Bluche, 1990, p.165).

[12] (Church, W.F. National Conciousness, History and Political Culture in Early Modern Europe, 1975, p.57).

[13] (Church, W.F. France. Ranum O. Edit. 1975, pp.43-66).

[14] (Sutton, G.V. Science or a polite society, Westview Press, 1995).

[15] (Vol.22, pp.525-576 and Brugmans H.L. Le Séjour de Christiaan Huygens à Paris. Paris, 1935).

[16] (Vol.22, pp.536-9).

[17] (Vol.2, pp.165-6, 169, 173-8, 287, 453, 494-7. Sutton, 1995, p.111).

[18] (Molière, les femmes savantes, Act II, Classics Larousse, 1972).

[19] (Molière, les femmes savantes, Act.III).

[20] (Vol.5, p.486).

[21] (Vol.4, p.325).

[22] (lost but mentioned by Chapelain, Vol.4, p.119).

[23] (Vol.4, p.416).

[24] (Vol.4, p.416).

[25] (Vol.5, p.25).

[26] (Chapelain's, Vol. 4, p.416).

[27] (Vol.4, p.367).

[28] ("Au Sieur Huygens, Hollandois, grand mathématicien, inventeur de l'horloge de la pendulle......1,200 livres". Vol.4, p.390).

[29] (Vol.5, p.375).

[30] (Martha Orstein, The Role of Scientific Societies in the Seventeenth Century. New York, 1913, pp. 165-186).

[31] (Stroup, 1987, p.56-63).

[32] (Stroup, A. 1987, pp.10-20).

---

[33] (Middleton, 1964, p.61-2).

[34] (Alice STROUP, Royal Funding, Transactions of the American Philosophical Society, Vol.27, Part 4, 1987, p.69).

[35] (S.Schaffer's talk on science in the 17th century at the Whipple Museum. Cambridge. 16.10.1986).

[36] (Vol.6, pp.95-6).

[37] (G.Hanataux. Histoire de la Nation Française. Vol.14. Chapitre II. Paris, 1923).

[38] (Brugmans, 1935, pp.119-171).

[39] (Pierre GAUJA, Les Origins de l'Académie des Sciences de Paris, in : Gauthier-Villars edit. Institute de France. Académie des Sciences Troisième Centenaire, 1666-1966. Paris, 1967, pp.1-55).

[40] (Lucien Plantefol: Fondation et Premières Années, in Gauthier-Villars edit. Académie des Sciences Troisième Centenaire...1967, p.59).

[41] (McKie, D. The Early Years of the Académie des Sciences, Endeavour, 1966, 25, pp.100-3).

[42] (Hahn, R. The Anatomy of a Scientific Institution. The Paris Academy of Sciences, 1666-1803.University of California Press. 1971, p.31).

[43] (Vol.22, pp. 526-576 & Brugmans, 1935, pp.119-171).

[44] (Vol.5, p.483).

[45] (Vol.5, p.493).

[46] (Vol.4, p.325-9).

[47] (Patent Royal, 13 May 1663, Vol.4, p.342-3).

[48] (Vol.5, p.267, 271, 276, 279, 285, 286).

[49] (Middleton, W.E.K., A Footnote to the History of the Barometer, Notes & Records of the Royal Society, Vol. 20, 1965, p.145).

[50] (Taylor, E.G.R., 1970, p.95).

[51] (Vol.21, p.105-8).

[52] (Mémoires de Mathematique et de Physique par Messieurs de l'Académie Royale des Sciences, Extraits des Journaux des Sçavans. Vol.X, MDCCXXX, pp.505-7).

[53] (Vol.9, pp.91, 96, 167).

[54] (Mémoires... Vol.X, p.472-5).

[55] (Mémoires... Vol.X, pp.482-6; and Picard on observations of Saturn, 487-8; 491-4; 505-7; on air-pump experiments, 529-536; on Saturn, 537-9; on a new lever, 540-4; on portable watches "*l'invention consiste en un ressort tourné en spirale*", 549-550; 624-8; on how to prove the *justesse* of the lever, 629-632; against Catalan's attacks on the Horologium Oscillatorium, 634-6).

[56] (Stroup, 1987, pp.22-3).

[57] (R.Pere J.B. de la Granje, Les principes de la philosophy, Descartes, Rohault, Regius, Gassendi, le P.Maignan, Paris, 1675).

[58] (published by Samuel Clarke.. on Rohault's physics, Six Philosophical Dissertations, Cambridge by Fletcher & Hodson, 1770).

[59] (Leopold, J. Christiaan Huygens, the Royal Society and Horology, Antiquarian Horology, Autumn, 1993, pp.37-42).

[60] (Vol.2, pp.1-2).

[61] (Vol.2, pp.146-7).

[62] (Vol.2, p.142,165-6, Huygens to Chapelain, p.169, Chapelain to Huygens, 173-6, on the *balancier*, pp.176-7).

[63] (Vol.2, p.157).

[64] (18th April, Vol.2, p.169).

[65] (Vol.2, pp.1-2).

[66] (Leibniz' Acta Eruditorum, June 1686, Vol.10, p.156).

[67] (Herivel J. The Background to Newton's Principia, Oxford, Clarendon Press, 1965, p.132).

[68] (Vol.9, p.333; Vol.10, p.212).

---

[69] (Vol.9, p.392: Locke's An Essay concerning the human understanding, Book II, Chapter XIII, London, 1690).

[70] (Vol.4, p.327).

[71] (Racine, Oeuvres Complétes, 1821, p.9).

[72] (Vol.8, p.198).

[73] (to his brother Constantijn 23 June 1663, Vol.4, p.361).

[74] (Vol.5, p.185).

[75] (Traité de la Percussion ou chocq des Corps, dans lequel les principales regles du movement, contraires à celles que Mr.Descartes..., Vol.16, pp.207-8).

[76] (Vol.18, p.668).

[77] (Vol.7, p.431).

[78] (Mémoires de l'Académie... Vol. X, p.163).

[79] (Vol.11, pp.91-238).

[80] (Chamberlayne, Mémoires de l'Académie... J.Innys, London,1721, pp.29-30).

[81] (Vol.18, pp.74-81).

[82] (Vol.18, p.76).

[83] (Bluche, 1990, p.241-9).

[84] (Racine J., Oeuvres Complètes de Racine, vol. II, 1960).

[85] (Sonnino, P. Louis XIV and the Origins of the Dutch War, Cambridge U.P.1988, pp.3-7).

[86] (Pennington, D.H., Europe in the Seventeenth Century, 1990, p.512).

[87] (Maland, D. 1984, p.309).

[88] (Pennington, D.H. 1990, p.512 & Maland D. 1984, p.307).

[89] (Stoye, J. Europe Unfolding 1648-88, 1988, pp.367-9).

[90] (Stoye J., 1988, p.374).

[91] (Ashcraft. Revolutionary Politics. Princeton, 1986, p.11).

[92] (Usher, A.P.. A History of Mechanical Inventions. New York, 1988, pp.28-29).

[93] (Schaffer, Newtonianism, in: OLBY R.C. and CANTOR G.N. edit. Companion to the History of Modern Science. London. Routledge, 1990, p.616).

[94] (Stroup, 1987, p.55).

[95] (Vol.22, p.p221-2, for questions from the audience: pp.223-4).

[96] (November, 1666, Vol.6, p.90).

[97] (Vol.3, pp.238-9).

[98] (Colbert, Instructions et Mémoires. Vol.5: Fortifications, Sciences, Lettres Beaux-Arts, Bâtiment. Paris 1868. LXII).

[99] (Vol. 4, p.369).

[100] (Vol.4, pp.167-170).

[101] (Gyel, P. History of the Low Countries: Episodes and Problems, The Trevelyan Lectures, London Macmillan & Co. 1963. Lecture 4).

[102] (According to Schama, Louis wanted to reduce the "treacherous Dutchmen" to sign a treaty which would make them pay their "due submissions" then and later. Schama, S. 1988, p.274).

[103] (Struik, J.D. Het land van Stevin en Huygens. Chapter 8. Nijmegen, 1979, pp.97-108).

[104] (Treasure, G. The Making of Modern Europe, 1648-1780. 1985, p.474).

[105] (Hunter, M. The Crown, the Public and the New Science, 1689-1702. Not. Rec. R. Soc. Lond. 1989, Vol.43, pp.99-116).

[106] (Schaffer, Wallifaction: Thomas Hobbes on School Divinity and experimental pneumatics. Studies in Hist. of Phil. of Sci. Vol.19, 1988, pp.275-298).

[107] (Vol.8, pp.553-4. January 1685, Vol.9, pp.1-2).

[108] (Vol.9, pp.3-4).

[109] (Drake, S., Galileo, OUP, 1980, p.10).

[110] (Sarton, G. Second Preface to Vol.38. The Study of Early Scientific Textbooks. ISIS, 38, 1947, pp.137-143).

[111] (Hunter, M. Science and the shape of orthodoxy, the Boydell Press, 1995, p.103).

---

[112] (Vanpaemel, G.. Rohault's Traité de Physique and the teaching of Cartesian Physics, Janus, 1984, pp.31-9).

[113] (Turner, A. 1987, pp.172-3).

[114] (Westfall, 1971, pp.424-512).

[115] (Vol.5, p.48, 124).

[116] (Hunter, M. Science and Society in Restoration England. Cambridge U.P.1981, p.87).

[117] (Keller, A. Technological aspirations and the motivation of natural philosophy in seventeenth century England. Hist. of Tech. 1993, Vol.15, pp.76-92).

[118] (Schaffer, Natural Philosophy, in Rousseau & Porter, 1980, pp.55-91; Shapin, Social uses of science, ibid. pp.92-139).

[119] ("elles son toutes tirées par la nature. Nous ne faison qu'énoncer des phénomènes conjoints dont la liaison est ou nécessaire ou contingente, phénomènes qui nous sont connus par l'expérience: necessaires en mathématiques en physiques et autre sciences ces rigoureuses: contingents en morale, en politique et autre sciences conjecturales" D.DIDEROT. D'Alembert's Dream. Oeuvres Complètes, 25 Vols, Tome XVII, Hermann, 1975, p.109).

[120] (Diderot, Oeuvres Complètes, Tome IX, Hermann, 1975)

[121] (Voltaire, Eléments de la philosophie de Newton, in: Les Oeuvres Complétes de Voltaire. Oxford Voltaire Foundation, 15, 1992).

[122] (Bachelard, S.L'influence de Huygens au XVIIIe et au XIXe siécles. In: Huygens et la France, Paris, Vrin, 1981, pp.241-258).

CONCLUSION

It can be concluded that Huygens was a pioneer in mechanical engineering. Everything in his approach seems to lead to that conclusion. He thought of a new invention, the pendulum clock, designed it, built a model and experimented with it to see the applicability of the idea. He then discussed it with an instrument maker, who introduced his expertise to improve the designs. When a satisfactory working instrument was eventually constructed, Huygens began to employ it in measurements, comparing the results with those given by existing devices. Realizing that the pendulum had made clocks more accurate than ever before, he proceeded to consider further improvements. Cheeks were tried to see if he could reduce the error introduced by the swing of the pendulum. He did not find the right shape immediately, but designed on paper what it would look like applying Archimedean geometry. He found that he needed to build two cycloidal cheeks. Then, supplying the appropriate explanation, Huygens had another model made by the instrument maker, who would also try different lengths and shapes to improve the model. The cycloidal cheeks achieved what Huygens had sought an isochronous and more precise pendulum clock. It was the first precise instrument produced to measure time and both Huygens and Coster contributed to its improvement. Huygens had the idea and tried the first model. Coster was a good clockmaker, working with good materials and accuracy. Huygens went further and introduced calibration methods by using two instruments together not realizing the experiment was wrong because eventually they worked in synchrony due to their proximity and not because of their accuracy. However, these experiments show that he was looking for what he called "*justesse des horologes pour les tenir dans* *l'accord perpetuel*"[1]. To all this Huygens added an underlying geometrical theory, to explain it scientifically to the learned society of the time, and to demonstrate empirically its applicability and usefulness.

Furthermore, the "facts" drawn from Huygens' manuscripts show the 'mechanical engineer' not only because of the theories that may explain his most important instruments, but also all the important aspects of mechanical engineering such as the use of materials, the various designs of parts of each model and what may be one of his main characteristics: the design of specific methods and standard experiments to test for accuracy and precision even if they were "wrong" for our standards.

Huygens was therefore a pioneer in presenting a complete work on mechanics which explained instruments, or 'automata (as he called the clocks) by mathematical axioms and laws. The Horologium Oscillatorium of 1673, was a book that inspired others to develop a tradition of mechanics for the mechanical engineer. With geometrical ratios he was able to show the applicability of technology to major practical problems. This had never been done before. He went further than any of his contemporaries did and defined an instrument of precision, namely the pendulum clock. John Wilkins and John Dee in England had suggested this[2]. Wilkins said that mathematics should be used in the mechanical arts[3]. The pendulum clock did that and more. It introduced a more modern and advanced technology than that available in the seventeenth century and which in later years would inspire a new field in technology: mechanical engineering.

Huygens clearly felt completely at ease with mechanics and geometry in explaining how automata worked; he drew on a tradition of geometry, which went back to the Greek Atomists and geometers, in particular, Archimedes. It was, however, quite a different matter to explain new concepts and physical phenomena in other fields of knowledge, without relying on some underlying philosophy as had been done hitherto. Huygens bridged both worlds, the old philosophical debates about the composition of the elements and their motion, and the new mechanical basis to explain that the physical world, and indeed the universe, moved in a perfectly symmetrical way which could be compared to mathematical ratios. He pioneered a tradition where nature could be explained in purely physical terms without a Creator's intervention. Nature existed as such and its laws could be discerned independently of religion, metaphysics, or philosophy and without the metaphysical debate so far used also by contemporary scientists who defined themselves as natural philosophers.

It was the beginning of a new age in science. Empirical sciences explained natural phenomena and helped to define the physical properties of natural elements. The experiments carried out by Huygens led him to prove certain hypotheses and to create new theories. His theory of matter emerged from the need to elucidate the new phenomena, especially, those produced by the air pump. Christiaan's studies on the air pump present the experiments carried out 'per se' with the corresponding designs. Then he tried to define the phenomena observed by developing his own 'physical' theory based on Cartesianism, but in particular, on atomism and his studies on statics and dynamics supported his theories. He went further than his contemporaries in that he developed a "scientific methodology" based in facts rather than argumentation. He did not 'collect information' in a Baconian way, but created data from his experimentation with the clock and the air pump that could be compared, analyzed, studied and improved again.

Huygens developed a new way of thinking in mechanics and physics with his theory of impelled or inherent motion and, most importantly, with his theory of relativity for uniform and accelerated motions. His theory of relativity of motion needed further research, but he was inhibited because he was unable to deduce all the physics he needed; there was still a strong philosophical association with scientific studies. In view of what I have discovered about Huygens, the statement from some historians that Huygens left something when he did not fancy it, is open to objection. Instead it could be said that when certain observations were difficult to fit into his mechanical or his physical/atomistic theories, he tried to find solutions looking at other physical theories; if this still did not work, electricity was an example of this, he left it at that. There were other limitations to his work, which have to be acknowledged. He did not believe in action at a distance and continued to believe that his concept of pesanteur, maybe a difficult concept to comprehend nowadays, was good enough to describe the fall of bodies. It seems the right conclusion when looking at his division of matter into degrees of different sizes of particles with specific physical properties. Unlike Descartes, he did not search for the primary principles that underlined a world created by God.

Huygens was more of a "scientist of nature", a natural scientist capable of developing a scientific methodology from the experimental data. Above all, he should be seen as an engineer, because he wanted both to make the best working model for any of the instruments he designed and also to explain their operation by geometry rather than debating its feasibility. Theories and designs accompanied by measurements and which others could use to create or invent similar instruments. According to Usher and Pacey[4], the seventeenth century was a very important period in witnessing the foundations of a new form of engineering. It could be added that this was a new field not only fully based on mathematics but on design and measurements of the instrument, essential patterns for an engineer to follow and the study of better materials.

He also tried to achieve accuracy with the experiments carried out on the air pump. Furthermore, being a manual instrument, it had to be easy to handle to avoid any degree of error. It was a very different instrument from the clock. There was a great difference in methodology and design and it was comparatively easy to use Archimedean geometry as the basis for a mechanical explanation of the clock. It was easier to improve because Huygens could use geometry to introduce any appropriate changes. However, the air pump had to yield certain results before any of its parts could be transformed. With this instrument, observation was essential to evaluate the phenomena obtained and to assert what new designs were required. The clock was an automaton kept in motion once it was wound up with an in-built mechanism of wheels and pulleys, capable of giving precise measurements. However, with the air pump it was difficult to know how a new improved model was better than the previous one, unless the observer had expertise in the experiments and knew what results to expect when using the instrument. The air pump had many factors which had to be taken into account at any one time and which could not be recorded with precise numerical values. It was a physical machine yielding results, which could be observed directly and in greater variety than a precision instrument. It was much more versatile than the clock. Furthermore, the air pump required specific skills to make it work well every time, whereas the clock only required winding and would go on its own. Clocks were used daily in the household and in science, in particular, astronomy and the measure of longitude, or simply, for precise measurement. However, a variety of machines and artifacts as well as methods for new experiments derived from the air pump. For instance, the steam-engine developed from the work by Huygens, but mostly by Papin, on the use of gunpowder explosions and the boiling of water in a vacuum in the gunpowder cylinder.

For all their uses, European courts did not encourage the invention of new instruments for gunnery only. After the discovery of the Americas, with the riches that could easily be acquired by shipping and without war a new and important development in the history of economics took place. Instruments such as the clock, if used at sea, could help ships to get to port safely and faster, therefore, improving the chances of good commerce. The new instruments would help a court not only to gain power, but also to enlarge the Treasury, with the consequent impact in the economics of a country.

Huygens preferred the mechanics of the clock, which allowed him to predict geometrically the changes to be introduced in this instrument of precision. It does not mean that he gave up on other instruments in desperation. On the contrary, he foresaw a totally different and new field of science, which was challenging enough to make him write several treatises, trying to explain the physical properties of the devices he invented and designed. For this reason, the air pump was crucial for Huygens' own physical theory. He was led to compose a variety of treatises on statics, dynamics, gravitation, pesanteur and cosmology. He was trying to explain the physical properties of the phenomena observed during those studies. Unlike contemporaries, Huygens defined nature in mathematical ratios and matter through the physical concept of motion of its particles. His theory of matter linked with his cosmology and to his belief in the existence of other universes with planets similar to ours. Huygens was able to deduce a mechanical-geometrical theory for clocks and with this he could also deduce a theory either after or before trials. However, the air pump was only a one-way road. The outcome of the experiments dictated the creation of new theories of physics of matter. With this empirical instrument, it was through experimentation that theories developed, and not the other way round.

Some historians only mention past natural philosophers that they think relevant to today's science, rather than appreciating their contribution at the time. This is found mostly in general histories of science, where the view is too superficial (see bibliography) or lacking, physics or technology but also in the philosophy of science[5]. On the other hand, historians hardly ever recognize Huygens' influence on Newton. When Huygens is mentioned, one can read statements such as Cohen's: "witness the failure of Huygens to create a Newtonian synthesis". Indeed, nobody can create somebody else's system. The same could be said of any author before Newton, never mind Huygens[6]. Other historians only refer to him superficially, or rather partially referring only to one of Huygens' instruments[7]. Maybe it is time for historians to work on past authors in a deeper and more comprehensive manner, trying to create a fuller image of all their work. The various studies already in existence and aimed at specific subjects should be a good reference to complete Huygens' and many other authors' pictures in the history of scientific thought.

It is also wrong to fit authors into 'convenient categories'. For instance, Patterson shows Huygens, Wren and Hooke as belonging to the same group[8]. They are scholars with individual and very specific characteristics that must be taken into account. Also as Hunter says a more detailed study of less known scientists of the time is still pending[9]. Others fail to recognize[10] the importance of the use of in the seventeenth century. Huygens and colleagues referred to *experimento*, demonstration, examination. Furthermore, Huygens was aware of the difference between good and not so good experiments, to which he referred as "*experimento veritable*" and "*experimento vulgare*" respectively[11].

It would be interesting to see how science could develop so quickly and with such drastic differences of method -from philosophico-mechanical to purely mechanical- in less than fifty years. For that to happen, several authors were needed. Newton would not have reached the other side of the river without Huygens' bridge. However, Huygens' work needs further research to see how far each field advanced with respect to his contemporaries, rather than studying him in very small sectors of his work. More studies dealing with Huygens' work as a whole are necessary. Contrary to what some historians of science may consider being "well covered ground"[12], much remains to be done to achieve a greater understanding with historians who are conversant with both the scientific and the philosophical discourse of the time[13].

Huygens was disillusioned and sad towards the end of his life. He had lost the enthusiasm that had inspired him to create what he and his fellow colleagues of the Academy called a 'new and beautiful science'. His feelings may have been due to the lack of interest on his work on the part of the Academy, which he had admired so much. If only he had known how inactive this institution was from 1682 onwards, he may have felt differently. He had to defend his work against the criticism of Catelan, a not very capable mathematician, who could not understand Huygens' Horologium Oscillatorium. Catelan was Catholic, like the Court, and French, and his criticisms may have been taken seriously by the bureaucrats in charge of the Academy after 1683. I believe this was one of the reasons why Huygens' contract/pension was not renewed after Colbert's death, in addition to the economic difficulties the French administration was having, which did not allow for the expensive salaries of foreign members. Nevertheless, he could have been made a Fellow. Although Huygens had criticized, anonymously, the use of gunpowder for war; it must have been known he had written it, because of the support it won from Papin. In his opinion, this material should have been put to better use. But what they could not foresee in the seventeenth century was that, once an invention appeared in the market place, anybody could use it for purposes other than peace. The way the Academy released Huygens after Colbert's death was cruel. It was more a matter of misunderstandings and of a very biased bureaucracy, whose members may have hated Colbert as much as many citizens did and anything he had directed. There was no scientific reason for the dismissal.

Huygens was deeply admired by his contemporaries until his death. Bernoulli's letters show the big regard that members of the Academy still held for Huygens after 1683. Bernoulli wrote to French scientists and those from other countries, urging them to write to Huygens to encourage the solution of mathematical problems he had set[14]. Huygens was not a proud scientist maybe that is why he refused to create Huyguenian schools and a unified treatise of his work, as some contemporaries had suggested in their letters[15]. He admired the new science and fully appreciated how fast it could develop. He saw new ideas rapidly replacing others, which became obsolete, as was the case with Leibniz's calculus. It is therefore likely that he would not have thought that his own ideas would be used for reference for very long.

Huygens did not mention God in his mechanics. Automata could be created without God's intervention. He regarded the question of God's existence as beyond the powers of human understanding. For him, the idea of God surpassed any possible description or connection with his work[16]. He did not think it necessary to appeal to a Creator when he was at a loss. He regarded the world of human knowledge as simply human.

It can be concluded that Huygens contributed greatly to the development of a new field, namely mechanical engineering. It was Huygens who, like Galileo before him, used a geometrical foundation in his mechanics. Huygens took it further, and this geometry was the basis, which could simplify and give an accountable measure of nature and of any man-made instruments alike. Huygens did not use the arithmetical notation known today in most of the basic laws of mechanics, but he arrived at the same conclusions through geometry. Moreover, apart from the mechanical theories of the instruments he designed various models, tried different materials and standardized methods for their use, therefore, opening the door to the new field of mechanical engineering.

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[1] (Vol.5, p.243).
[2] (Middleton, 1964, p.36 and 38).
[3] (John Wilkins, Mathematical Magick, 1648).
[4] (Pacey A, 1980, p.131).
[5] (Holton G. Thematic Origins of Scientific Thought Kepler to Einstein, Harvard University Press, 1973. Cohen, I.B. The Birth of a New Physics, Penguin Books, 1987. Basalla, G. The Evolution of Technology, Cambridge History of Science Series, 1988. Kuhn, T. S, The Structure of Scientific Revolutions. The University of Chicago Press 1970).

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[6] (Cohen, I.B. The Newtonian Revolution, Cambridge University Press, 1983, p.158. Gjertsen, D. The Newton Handbook. Routledge & Kegan Paul, 1986, p.265).

[7] (Cohen, I.B. The Revolution in Science, Harvard University Press, 1985. Ruestow, E.G. Physics at 17th and 18th-Century Leiden, Martinus Nijhoff, The Hague, 1973).

[8] (Patterson, L.D. Pendulums of Wren and Hooke, 1952, Osiris, Vol.10, pp.277-321).

[9] (Hunter, M. 1981, p.69-70).

[10] (HELDEN, A.van & Hankins C. Instruments, Osiris, 1994, Vol.9, pp.1-6).

[11] (Vol.5, p.104, 241, 261).

[12] (Dr. Todd, direct communication, Christie's South Kensington, May 1996).

[13] (Hunter's use of "correct data" smacks of a lack of knowledge as to how the scientific community really describes data. Hunter, M. Science and the Shape of Orthodoxy. Intellectual change in late seventeenth-century Britain. The Boydell Press, 1995, p.103)

[14] (Chamberlaine edit. Mémoires of the Royal Academy of Sciences in Paris, Preface by Fontanelle. J.Innys, London, 1721, p.26).

[15] (Vol.10, p.404).

[16] (Vol.21, Que penser de Dieu? p.341-3).

PRIMARY SOURCES

ALFONSO X el Sabio, Libros de Saber de Astronomía, edited by Manuel Rico y Sinobas, Madrid, 1866.

BACON, Roger, Opus Majus, edit John Henry Bridges, Vol. I, Oxford, Clarendon Press, 1897.
Opera hactenus inedita Rogeri Baconi, some edited by Robert Steeel, Fasc. XVI, Oxford, Clarendon Press, 1909-1940.
Rogeri Baconis Opus Minus in F.R.Rogeri Bacon, edited by J.S.Brewer, London: Longman, Green, Longman, and Roberts, 1859.

BIRCH ,T. History of the Royal Society of London, 1705-1766, printed in facsimile New York & London 1968.

CHAMBERLAYNE, Mémoires of the Royal Academy of Sciences in Paris. Tome X, J. Innys, London, 1721.

COLBERT, Jean-Baptiste, Lettres, instructions et mémoires, ed. P.Clément. 8 Vols. Paris: Imprimerie impériale, Imprimiere nationale, 1861-70.

COLBERT, Instructions et Mémoires. Vol.5: Fortifications, Sciences, Lettres, Beaux-Arts, Bâtiments, Paris, 1868.

DESCARTES R., Oeuvres de Descartes (1596-1650). Publishers: Charles Adam and Paul Tannery. Paris, Vrin, 1974. The Principia in Vol.VIII, 1973.

DIDEROT, D. D'Alembert's Dream. Oeuvres Complètes, 25 Vols, Hermann, 1975.

FAURÉ-FREMIET, E. Les Origines de l'Académie des Sciences de Paris. Notes & Records of the Royal Society of London, 1966, 20, pp. 20-31.

FONTENELLE, B., Musée du Conservatoire National des Arts et Métiers, 1967: Histoire, Prestige de l'Académie des Sciences, 1666-1966.

GALILEO Galilei, Opere. Edizione Nazionale, edit. Antonio FAVARO. Firenze, Barbera, 1890-1907. Reprint 1929-1939. 19 Volumes and one of Indici.

GASSENDI, Pierre. Opera Omnia, "De vita et moribus, EPICURUS". Stuttgart-Bad Cannastatt, 1964, pp.173-236.
The Selected Works of P.Gassendi, translated by Craig B. Bush. Johnson Reprint Corporation, New York. 1972.

GUERICKE, Otto von. The new (so-called) Magdeburg experiments of Otto von Guericke, 1672. Translated by M. Glover Foley Ames. Kluwer Academic Publishers, 1994.

HOOKE, R. The Posthumous works of Robert Hooke. The sources of science, N.73. Johnson Reprint. N.Y. & London, 1969.
Micrographia, London, 1665.

Histoire de l'Académie royale des sciences depuis 1666 jusqu'à 1699. Fontenelle, B. edit. 2 Vols. Paris: Martin Coignard, Guerin, 1733. Vol.s 1-2 of Académie royale des sciences.

HUYGENS, Christiaan, OEUVRES COMPLÉTES, Volumes 1-22, Martinus Nijhof. La Haye 1888-1950.

JOURNAL des Sçavans, Paris and Amsterdam, 1665-99.

LOCKE, J. An Essay concerning the human understanding, Book II, Chapter XIII, London, 1690.
An Essay concerning human understanding, J.M.Dent & Sons edit, 1961.

MÉMOIRES de l'Académie Royale des Sciences. Depuis 1666 jusqu'à 1699. Tome X, A Paris par la Compagnie des Libraires (MDCCXXX). Avec le privilége du Roy.

MÉMOIRES of the Royal Academy of Sciences in Paris, Preface by Fontanelle. Chamberlaine edit.. J.Innys, London, 1721.

MERSENNE, P. Correspondence de P. Mersenne. Commercée par Mme Paul Tannery, publié and annotée par Cornelis de Waard, Paris, Vol.2 (1631-1633), Presses Universitaires de France, 1936.
Novae Observations physico-mathematicae, Paris, 1647.

MOLIÉRE, J.-B., Les Femmes Savantes, Classics Larouss, 1972.
The Misanthrope and other plays, Penguin Classics, 1987.
The Miser and other plays, Penguin Classics, 1985.

OLDENBURG, H. The Correspondance, edited by A.R.Hall & M.Boas Hall. 10 Vols. Madison, Wisc.: University of Wisconsin Press, 1965-75.

RACINE, J. Britannicus, Bordas, 1984.
Iphigénie, Bordas, 1984.

ROHAULT, M. published by Samuel Clarke.. on Rohault's physics, Six Philosophical Dissertations, Cambridge, Fletcher & Hodson, 1770.
Traité de Physique, Paris, 1676.
Entretiens sur la philosophie, Paris 1671.

Mdme de SÉVIGNÉ. Correspondance, Vols.1 and 2, Gallimard 1972.

STEVIN, Simon, The principal works of Simon Stevin, (Amsterdam C V Swets & Zeitlinger) Vol.I Mechanics, edited by E.J.Dijksterhuis, 1955; Vol.IIA and IIB on Mathematics, edited by D.J.S.Truik, 1958; Vol. V, Engineering, edited by R.J.Forbes, 1966.

Van SCHOOTEN, F. Geometria, Amstelodami, 1683.
On Descartes' Geometry, manuscript at Cambridge Library: M.6.69.

VOLTAIRE, Les Oeuvres Complétes de Voltaire, Oxford Voltaire Foundation. 2 Vols, 15, 1992.

WHITESIDE, D.T. The preliminary manuscripts for Isaac Newton's 1687 Principia, 1684-1686, Cambridge University Press, 1989.

The Mathematical Papers of Isaac Newton, 8 Vols. (Vol.6 1684-7) Cambridge University Press, 1967-81.

SECONDARY SOURCES

ALLEN, B. Reversing centrifugal forces, Nature, Oct. 1990, Vol.347, pp.615-6.

ASHCRAFT. Revolutionary Politics. Princeton, 1986.

ASHLEY, M. A History of Europe 1648-1815. Prentice-Hall, New Jersey, 1973.

BAILLIE, G.H. Watches their history, decoration, and mechanism. NAG Press Ltd., 1979.
Watchmaker and Clockmakers of the World. N.A.G. Press Ltd. London, 1976.

BARROW, I. Archimedes Opera. Londini, 1675.

BARTHOLINI, E. Selecta Geometrica, Hauniae, 1674.

BASALLA, G. The Evolution of Technology, Cambridge History of Science Series, 1988.

BAUMGARTNER, F.J. Starry Messengers: supernovas, Comets and Sunspots Heralded the Scientific Revolution. The Sciences, Jan/Feb, 1992, pp.39-43.

BEARD, G. The Work of Christopher Wren, Bloomsbury Books London, 1982.

BEDINI, S.A. Science and instruments in seventeenth century Italy. Variorum, 1994.
The Pulse of Time: Galileo Galilei the determination of longitude and the pendulum clock, [Firenze]: L.S.Olschki, 1991.

BEIK, W. Absolutism and Society in XVIIth Century France, Cambridge U. P., 1985.

BELL, A.E. Christiaan Huygens, and the development of science in the seventeenth century, London, 1947.

BENNETT, J. Geometry and surveying in early seventeenth century England. Annals of Science, 1991, Vol.48, N.4, pp.345-354.
Christopher Wren: Astronomy, Architecture and the Mathematical Sciences, Journal for the History of Astronomy. 1975, Vol.6, pp.149-184.

BERTHOUD, F. Histoire de la mesure du temps apres les Horloges. Tome 1, Berger-Levrault, 1976.

BLACKWELL, R.J. translates: Christiaan Huygens. The pendulum clock or geometrical demonstrations concerning the motion of pendula as applied to clocks. With an introduction by BOS, H.J.M. The Iawa State University Press, AMES, 1986.

BLUCHE, F. Louis XIV vous parle, [France], Stock, 1988.
Louis XIV, Oxford, Basil Blackwell, 1990.

BOS, H.J.M. edit. Studies on Christiaan Huygens, Swets & Zeitlinger B.V.1980.

BOULENGER, J. The Seventeenth Century, London, W. Heineman, 1930.

BOUTROUX, P. L'enseignment de la mécanique en France au XVIIe siècle. ISIS, 1922.

BOYER, C.B. A History of Mathematics, Princeton University Press, 1985.

BRITTEN, F.J. Old Clocks and Watches, 9th edition, 1982.
Britten's Old Clocks and Watches and their makers. London 1956.

BRUGMANS, H.L.Le Séjour de Christiaan Huygens à Paris. Journal de Voyage à Paris et à Londres, Paris, 1935.

BRUTON, E. The History of Clocks and Watches. Orbis Publishing, 1979.
Dictionary of of Clocks and Watches. Arco Publications, 1962.

BURCH, Ch.B Huygens' pulse models as a bridge between phenomena and Huygens' mechanical foundations, Janus, 1981, 66, pp.53-64.

CASINI, P. Newton: The Classical Scholia, Hist. Sci. 1984, 22, pp.1-58.

CENTORE, F.F. Robert Hooke's Contributions to Mechanics: a study in 17th century natural philosophy. Martinus Nijhoff. The Hague, 1970.

CHURCH, W.F. National Conciousness. History and Political Culture in Early Modern Europe, 1975.
France. Ranum O. Edit. 1975.

COHEN, I.B. The Birth of a New Physics, Penguin Books, 1987.
The Revolution in Science, Harvard University Press, 1985.
The Newtonian Revolution, Cambridge University Press, 1983.
'Quantum in se est': Newton's concept of inertia in relation to Descartes and Lucretius. Notes and Records of the Royal Society, 1964, 65, p.131-155.

COLLINS, H. Changing order: Replication and induction in scientific practice, London, 1985.

COOKE, C.W. Automata Old and New. N.XXIX, London MDCCCXCIII, in: Music and Automata. From Horology to Mechanical Musical Instruments. Sept. 1987, Vol.3, N.9, pp.81-111.

COOPER, J.S. For Commonwealth and Crown: English gunmakers of the seventeenth century, Wilson Hunt, 1993.

CROMBIE, A.C. Historia de la Ciencia: De San Agustin a Galileo, Vol.2, Alianza Universidad, 1980. Original title: Agustine to Galileo. Vol.II.

CROSLAND, M.P. The Emergence of Science in Western Europe, London and Basingstoke: Macmillan, 1975.

DARMSTAEDTER, L. Handbuch zur geschichte der naturwissenschaften und der technik, Berlin, 1908.

DAUMAS, M. Scientific instruments of the Seventeenth and Eighteenth Centuries and their Makers. "The Invention of the Seventeenth Century". London, 1972, pp.27-88.
Histoire Générale des Techniques, P. Universitaires de France, 1965, Vol. II.

DAVIS, E.A. Science in the making. 4 volumes, Taylor and Francis, 1995.

Dictionary of Scientific Biography, Charles Coulshon Gillispie et al edit. 16 Vols, New York, Scribner, 1970-1980.

Dictionary of the history of science. Edit. Bynum, W.F.; Browne, E.J.; Porter, R. Macmillan, 1983.

DIJKSTERHUIS, E.J. Ch.Huygens. Bij de Voltooing van zij oeuvres, Haarlem, 1951.

DRAKE, S. Galileo, OUP, 1980.
Galileo at Work: his scientific biography. NY.Dover Publications, 1995.

DUGAS, R. A History of Mechanics. N.Y.1988.

ELKANA, Y. edt. The Interaction Between Science and Philosophy, The Hebrew University of Jerusalem, 1974. Cohen B. Newton's Theory Vs. Kepler's Theory and Galileo's Theory: An example of a difference between a philosophical and a historical analysis of science, pp.299-338.

FAUVEL J. Flood R. Shortland M. Wilson R. edit. Let Newton Be!, Oxford Unversity Press, 1988.

FAUVEL, J. and GRAY, J. edit. The History of Mathematics, a reader. Macmillan Press & the O.U. 1987.

FOURNIER, M. Huygens' Designs for a Simple Microscope. Annals of Science, 1989, 46, pp.575-596.

GABBEY, A. Force and Inertia in Seventeenth-Century Dynamics. Stud. Hist. Phil. Sci., 1971, 2 , n.1, pp.1-67.

GAUJA, P. Les Origins de l'Académie des Sciences. Troisiéme Centenaire, 1668-1966, 2 Vols.2. Plantefol, L. "La fondation et les premières années", pp.59-72.

GAUTHIER-VILLARS edit. Institute de France. Académie des Sciences Troisième Centenaire. 1666-1966. Paris, 1967.

GENT, R.H. and HELDEN, A.C.van, Een Vernuftig geleerde, Museum Boerhaave, Leiden, 1995.

GJERTSEN, D. The Newton Handbook.Routledge & Kegan Paul, 1986.

GLANZ, J, Is the dark matter mystery solved? Science, February, 1996, Vol.271, pp.595-6.

Great Engineers and Pioneers in Technology. Editors: Turner Roland & Goulden Steven L. Vol.1, N.Y. St. Martin's Press, 1981.

GYEL, P. History of the Low Countries: Episodes and Problems, The Trevelyan Lectures, London Macmillan & Co. 1963. Lectures 1-4 and 6-8.

HACKMANN W. Electricity from glass: The History of the Frictional Electrical machine 1600-1850. Sijthoff & Noordhoff, The Netherlands, 1978.

HAHN, R. The Anatomy of a Scientific Institution. The Paris Academy of Sciences, 1666-1803.University of California Press. 1971.

HALL, A.R. The Revolution in Science, 1500-1750, Longman, 1984.

Horology and criticism: Robert Hooke, Studia Copernicana, 1976, Vol.16, pp.261-81.

Newton on the Calculation of Central Forces. Ann. of Sci. 1957, Vol.3, No.1, pp.62-71.

Robert Hooke and horology, Notes and Records of the Royal Society of London, 1951, Vol.8, pp.167-77.

Newton in France: A New View, Hist. Sci. 1975, 13, pp. 233-250.

HANATAUX, G. Histoire de la Nation Française. Vol.14, Paris, 1923.

HANSON, N.R. Patrones de descubrimiento, observación y explicación. Alianza Universidad, 1977. Original title: Observation and Explanation: A Guide to Philosophy of Science.

HELDEN, Anne C., The age of the air-pump, 1991, Tractrix 3, pp.149-172.

Theory and Practice in Air-Pump Construction: The Cooperation Between Willem Jacob's Gravesande and Jan van Musschenbroek. Annals of Science, 1994, 51, pp.477-495.

HENRY, J. Matter in Motion. Open University Thesis, 1983.

HERIVEL J. The Background to Newton's Principia, Oxford, Clarendon Press, 1965

Newton's Discovery of the Law of Centrifugal Force, ISIS, 1960, Vol.51, pp.546-553.

HESSE, M. Hooke's Vibration Theory and Isochrony of Springs, ISIS, 1966, Vol.57, 4, N.190, pp.433-441.

Hooke's Philosophical algrebra, ISIS, 1966, Vol.57, pp. 67-83.

HILL, C. The Century of Revolution, 1603-1714, Van Nostrand Reinhold, UK, 1987.

The World Turned Upside Down, Penguin Books, 1975.

HOBBES, T. Leviathan, Penguin Classics, 1986.

HOFFMANN, B. Relativity and Its Roots, Scientific Ametican Books, 1983.

HOLLISTER-SHORT, G.J. Gunpowder and mining in sixteenth- and seventeenth-century Europe, Hist. Tech. 1986, 10th annual volume, pp.31-66. Edited by N.Smith.

HOLTON, G. Thematic Origins of Scientific Thought. Kepler to Einstein. Harvard University Press, 1973.

HOSKIN, M.A. Newton, providence and the universe of stars, JHA, 1977, Vol.8, pp.77-101.

HOVING, A.J. Seventeenth century Dutch ship decoration. Model Shipwright, 1988, N.64, pp.30-34.

HOWSE, D. The Tompion clocks at Greenwich and the dead-beat escapement. Antiquarian Horology, Dec.1976, pp.18-34.

HUNTER, M. Science and Society in Restoration England. Cambridge U.P.1981.

The Crown, the Public and the New Science, 1689-1702, 1989, Not. Rec. R. Soc. Lon. 43, pp. 99-116.

Science and the Shape of Orthodoxy. Intellectual change in late seventeenth-century Britain. The Boydell Press, 1995.

and SCHAFFER, S. edit: Robert Hooke. New Studies. The Boydell Press, 1989 (with papers by: J.A. Bennett, M. Wright, J.T. Harwood, J. Henry, S. Shapin).

HUTCHINGS, D. Late Seventeenth Century Scientists, Pergamon Press, 1969.

HUTCHISON, K. What happened to Occult Qualities in the Scientific Revolution? ISIS, 1982, 73 (267) pp 233-267.

HUYGENS et la France. Table Ronde du Centre National de la Recherche Scientifique, Paris 27-29 mars 1979. Paris, Vrin, 1981.

ILIFFE, R. "In the warehouse": privacy, property and priority in the early Royal Society, Hist. Sci. 1992, 30, pp.29-68.

JACOB, M.G. Newton and the French prophets: New evidence. Hist. Sci, 1978, Vol.16, pp.134-142.

JACOB, M.C. Early Newtonianism, Hist. Sci., 1974, Vol.12, pp.134-142.

JOHNSTON, S. Mathematical practitioners and instruments in Elizabethan England. Annals of Science, 1991, Vol.48, pp.319-344.

JONES, J.R. Country and Court, England 1658-1714, Edward Arnold, 1978.

JURRIAANSE, M.W. the Founding of Leyden University, Leiden, E.J.Brill, 1965.

KELLER, A. Technological aspirations and the motivation of natural philosophy in seventeenth century England. Hist. of Tech. 1993, Vol.15, pp.76-92.

KENNY, A. Philosophical Letters. Descartes, Oxford University Press, 1970.

KING, G. The history of the telescope. Dover Publications, N.Y. 1979.

KNUTSSON, J. A seventeenth century collection of rose engines and tools: notes on the turning room at Skokloster. Sweden. Tools and Trades, 1990, Vol.6, pp.10-22.

KOYRE, A. Del mundo cerrado al universo infinito, Siglo XXI, Spain, 1979. Original title: From the closed world to the infinite universe, John Hopkins University Press, 1957.

KOYRÉ, A. Études Newtoniennes, Éditions Gallimard, 1968.
Estudios de Historia del Pensamiento Científico, Siglo XXI, 1977. Original title: Etudes d'histoire de la pensée scientifique.

KUHN, T. S, The Structure of Scientific Revolutions. The University of Chicago Press, 1970.
The Copernican Revolution, Harvard University Press, 1981.

LAIN ENTRALGO P., LOPEZ PINERO, J.M. Panorama histórico de la ciencia moderna, Madrid, 1962.

LATOUR, B. Science in action: How to follow scientists and engineers through society, Milton Keynes, 1987.

LEOPOLD, J.

Christiaan Huygens and the instrument makers. Studies on Christian Huygens, Bos, H.J.M. et al edit. Lise, Swets & Zeitlinger B.V.1980

Christiaan Huygens, the Royal Society and Horology, Antiquarian Horology, Autumn, 1993, pp.37-42.

LEWIS, M.J.T. The Greeks and the early windmills, Hist. Tech. 1993, Vol.15, Mansell, pp.141-189.

LLOYD, H.A. Some Outstanding Clocks (1250-1950), London, 1958.

MAANEN, Jan van. Seventeenth century instruments for drawing conic sections. Mathematical, 1992, Vol.76, N.476, pp.222-230.

Machines et Inventions approuvées par l'Académie Royale des Sciences depuis son établissement jusqu'à présent; avec leur description. Dessinées et publiées du consentement de l'Académie, par M. Gallon, Vol.I, Paris, G. Martin. 1735.

MAFFIOLI, C.S. Out of Galileo: the Science of Waters.1628-1718. Rotterdam: Erasmus Publishing, 1994.

MALAND, D. Europe in the Seventeenth Century, Macmillan, 1984.

MANCOSU, P. Philosophy of mathematics and mathematical practice in the seventeenth century. Oxford U.P. 1996.

MARCORINI, E. Editorial Director: Eléments d'histoire des sciences, Bordas, 1989.

McGuire, J.E. Force, Active Principles, and Newton's Invisible Real, Ambix, 1968, 15, pp.154-208.

McKie, D. The Early Years of the Académie des Sciences, Endeavour, 1966, 25, pp. 100-103.

McMullin, E. Newton on matter and activity, London, 1978.

Mémoires Scientifiques de Paul Tannery, 14 volumes. Published by J.L. Heiberg & H.G.Zenthen, Gauthier-Villars, Paris, 1912 to 1937.

MERTON, R.K. Science, technology and society in seventeenth-century England, New York; Harper & Row, 1970.

MILHAM, W.I. Time and Time-Keepers. Macmillan London, 1923.

MONTAGU, M.F.A. Studies and essays in the history of science and learning. New York, 1947.

MORRIS-SUZUKI, T. The technological transformation of Japan: from the seventeenth century. CUP, 1994.

MUSSON, A.E., Science and Technology in the Industrial Revolution, 1969, pp.26-30.

NEEDHAM, J. Ling, W., de Solal Price, D.J., Heavenly clockwork. The Great Astronomical Clocks of Medieval China, Cambridge U.P.1 986.

OLBY R.C. and CANTOR G.N. edit. Companion to the History of Modern Science. London. Routledge, 1990.

ORSTEIN, M. The Role of Scientific Societies in the Seventeenth Century.. New York, 1913, pp. 165-186. Chicago 1928.

PACEY, A. Technology in World Civilization, Basil, 1990.

PALM, L.C. & SNELDERS, H.A.M. edit.: Studies on the life of Antoni van Leeuwenhoek, 1632-1723. Amsterdam, Roposdi, 1982.

PARKER, G. The Dutch Revolt, Penguin Books, 1988.

PATTERSON, L.D. Pendulums of Wren and Hooke, Osiris, 1952, Vol.10, pp.277-321.

PENNINGTON, D.H. Europe in the Seventeenth Century, Longman, 1990.

ROUSSEAU, G.S.& PORTER, R. The Ferment of Knowledge. Studies in the historiography of eighteenth-century science. C.U.P. 1980.

RUDD, M.E. The long and the short of it: telescopes of the seventeenth century. Journal of the Antique Telescope Society. 1993, Vol.4, pp.12-19.

RUESTOW, E.G. Physics at 17th and 18th-Century Leiden, Martinus Nijhoff, The Hague, 1973.

SARTON, G. Second Preface to Vol.38. The Study of Early Scientific Textbooks. ISIS, 1947, 38.

Introduction to the history of science, 4 volumes. Baltimore, 1927-1948.

SCHAFFER, S. Wallifaction: Thomas Hobbes on School Divinity and experimental pneumatics. Studies in Hist. of Phil. of Sci. 1988, Vol.19, pp.275-298.

Scientific discoveries and the end of natural philosophy, Social studies of science, 1986, Vol.16, pp.387-420.

talk on science in the 17th century at the Whipple Museum. Cambridge. 16.10.1986.

Newtonian Cosmology and the Steady State, Cambridge University, PhD, 1980.

SCHAMA, S. The Embarrassment of Riches, W.Collins Sons and Co.Ltd. USA, 1988.

SCHIERBEEK, A, Antoni van Leeuwenhoek, zijn leven en zijn werken. Lochem, 1950.

SÉE, H. Les idées politiques en France au XVIIe siècle. Genève, 1978.

SERRES, M. A history of scientific thought, Blackwell, 1995.

SHAPIN, S. Closure and Credibility in 17th Century Science. Proceedings of the Manchester conference, 1988, pp.147-154.

The House of Experiment in Seventeenth-Century England. ISIS, 1988, 79, pp.373-404.

A social history of truth. Civility and Science in Seventeenth-century England. The university of Chicago Press, 1994.

Here and Everywhere: Sociology of Scientific Knowledge, Ann.Rev.Sociol. 1995, 21, pp.289-321.

and S.SCHAFFER, Leviathan and the Air-Pump, Princeton University Press, 1985.

SLANDES, D. Revolution in Time. Harvard University ress, 1983.

SNELDERS, H.A.M., Christiaan Huygens and Newton's Theory of Gravitation. Notes Rec.Soc. Lond., 1989, 43, pp. 209-222.

SONNINO, P. Louis XIV and the Origins of the Dutch War. Cambridge U. P. 1988.

STOYE, J. Europe Unfolding. Fontana Press, 1988.

STROUP, A., Royal Funding, Transactions of the American Philosophical Society, 1987, Vol.27, Part 4, pp.10-159.

STRUIK, J.D. Het land van Stevin en Huygens. Chapter 8. Nijmegen, 1979.

SUNG, Y-H. T'ien-Kung K'ai-wu: Chinese technology in the seventeenth century. Pennsylvania state University Press, 1966.

SUTTON, G.V. Science for a polite Society, Westview Press, 1995.

TATON, R. Les Origins de l'Académie Royales des Sciences. Paris: Presses Universitaires de France, 1965.
Histoire Génerale des Sciences, 4 Volumes, Presses Universitaires de France, 1966.

The History of Science and Technology, Facts on File, N.Y. 1980.

THIRY de Liége, A. Christiaan Huygens ses relations en Belgique. Horlogerie Ancienne, 1er Semester, 1995.

THORNDIKE, L. History of Magic and Experimental Science, Volumes 7-8, Columbia University Press, 1958.

TREASURE, G. The Making of Modern Europe, 1648-1780. 1985.

TUCK, R. Natural Rights Theories, their origin and development. Cambridge, University Press, 1981.

TURNER, A. Early Scientific Instruments Europe 1400-1800, Sotheby's Publications, Philip Wilson Publishers, 1987.

TURNER, G.L.'E. The History of Optical Instruments. Museum of the History of Science, Oxford, 1980.

USHER, P.A. A History of Mechanical Inventions. New York, 1988, and the 1990 editions.

Van GENT, R.H. & Van HELDEN, A.C.,. Een vernuftig gelerde, Boerhaave, 1995.

Van HELDEN, A. & HANKINS C. Instruments, Osiris, 1994, Vol.9, pp.1-6.And
Telescopes and authority from Galileo to Cassini, ibid. pp.7-29.
Van HELDEN, A. The Invention of the Telescope, Trans. Amer. Phil.Soc.1977, 67, 4, p.5+
The Historical Problem of the Invention of the Telescope, Hist. Sci. 1975, Vol.13, pp.251-263.

VANPAEMEL, G. Rohault's Traité de Physique and the teaching of Cartesian Physics, Janus, 1984, pp.31-9.

VILAR, P. Iniciación al vocabulario del análisis histórico. (The vocabulary for historical analysis). Editorial Critica, 1980.

WEBSTER, CH. The Great Instauration. Science. Medecine and Reform. 1626-1660. London, 1975.

WEINSTOCK, R. Dismantling a centuries-old myth: Newton's Principia and inverse-square orbits. Am.J.Phys. 1984, Vol.50, N.7, pp.610-617.

Newton's Principia and the external gravitational field of a spherically symmetric mass distribution. Am.J.Phys. 1984, Vol.52, N.10, pp.883-890.

WELD, Ch. R. A History of the Royal Society, 2 Vols. London, 1848.

WESTFALL, R.S. Never at Rest. A biography of Isaac Newton. Cambridge U P, 1988.

The Construction of Modern Science. Cambridge U P, 1977.

Force in Newton's Physics, New York, 1971.

Science and Religion in Seventeenth-Century England, Yale U.P.1958.

A note on Newton's demonstration of motion in ellipses, Arch.d'Histoire des Sciences, 1969-70, Vol.22-3, pp.51-60.

WHITESIDE, D.T. The mathematical principles underlying Newton's Principia Mathematica. JHA, 1970, Vol.1, pp.116-138.

Newton's early thoughts on planetary motion: a fresh look, B.J.H.S, 1964-5, Vol.2, N.6, pp.117-137.

Isaac Newton: Birth of a Mathematician, Not. Rec. Ro.Soc.London, 1965, Vol.20, pp.53-62.

Isaac Newton: The rise of a scientist 1661-1671. Not.Rec.Ro.Soc. London, 1965, Vol.20, pp.125-139.

WILLIAMS, T.I. The history of invention from stone axes to silicon chips, Macdonald & Co, 1987.

WILLMOTH, F. The genius of all Arts and the use of instruments: Jonas Moore (1617-1679) as a mathematician, surveyor, Annals of Science, 1991, Vol.48, N.4, pp.355-365.

WINTER, J. "Ch.Huygens": Les Inventeurs Célèbres, Lucien Mazenod, Paris 1962.

YATES, A. Giordano Bruno and the Hermetic Tradition, Routledge and Kegan Paul, 1978.

YODER, J.A. Unrolling Time, Christiaan Huygens and the mathematization of nature. Cambridge University Press, 1988.