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History of Physics and Related Sciences

Comments on the origin of pendulums: The controversy surrounding the pulsilogium

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This article presents a historical study on the evolution of the pendulum throughout the history of science; the pendulum is one of the most well-known instruments in physics. This device has been studied since the dawn of classical mechanics; however, little attention has been given to the process of its theoretical formalization. The pendulum did not always belong to the theoretical or conceptual domain of science; on the contrary, it was a common device for everyday use in various civilizations of the ancient and medieval world. It was only during the transition from the Middle Ages to the early Modern Age that the pendulum came to be recognized as an object of scientific interest, leading several scholars to dedicate themselves to the problem of pendular motion. In this article, we intend to discuss, among other topics, the invention of the pulsilogium, considered one of the first scientific instruments based on the pendulum, as well as the controversies that arose surrounding this device. More importantly, we examine the construction of the initial process of theorizing the pendulum, which occurred primarily between the 16th and 17th centuries, analyzing the methods employed by Renaissance physicists in their attempts to describe the dynamics of the pendulum, which were certainly beyond the scope of Aristotelian physics.
Keywords: The theoretical origins of the pendulum, Santorio Sanctorius, Paolo Sarpi, Pulsilogium.

1. Introduction

The pendulum is a highly significant scientific instrument in physics, not only because of its technical and theoretical importance, but also because it clearly illustrates how certain scientific concepts mature slowly over time. Although it is common to find historical accounts that attribute to Galileo Galilei (1564–1642) the primacy in the study of the pendulum, this narrative, while not entirely false, is incomplete. Galileo undoubtedly played a decisive role by systematically investigating the physical properties of the pendulum, establishing fundamental laws through the combination of observation, experimentation, and mathematization. In this sense, he can legitimately be considered the first to integrate the pendulum into the emerging science of his time; however, the path that led to these discoveries did not begin with Galileo, nor can it be properly understood without reference to the intellectual traditions that preceded him.

The roots of theorization about pendular motion go back to the late-medieval scholastic tradition, particularly to the debates developed between the 13th and 15th centuries concerning the nature of motion, the influence of weight, gravity, curvilinear movement, and so on. Medieval natural philosophers associated with Latin Aristotelianism reflected on periodic movements and oscillations, even though they did not possess a formal concept of the pendulum in the modern sense. In the transition to the Renaissance, these scholastic discussions did not disappear, but were reinterpreted within new intellectual practices. The growing interest in mechanical devices, clocks, scales, machines, weights, and counterweights, fostered empirical observation of regular and repetitive movements. The pendulum, although not fully theorized, began to be recognized as a phenomenon worthy of attention, especially in contexts related to timekeeping and practical mechanics.

In general, Galileo cannot be considered the first scholar to engage in the study of the pendulum, as there was already a group of thinkers before him interested in this question. However, it is Galileo's merit to have recognized in this seemingly simple object a phenomenon useful for investigating the laws of motion. By observing the regularity of its oscillations and by isolating properties such as isochronism (even if only approximately), Galileo transformed the pendulum into a conceptual instrument capable of linking sensory experience, mathematical abstraction, and theoretical idealization. Thus, the pendulum ceased to be merely a mechanical artifact of little interest and came to form part of the core of the new science of motion.

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Between the 15th and 16th centuries, the study of motion underwent a period of gradual change. Although Aristotelian physics remained the dominant theoretical framework for explaining natural phenomena, internal tensions and conceptual shifts began to emerge during this period, signaling a new way of interrogating nature. It is in this transitional context that the pendulum began to emerge as an object of scientific attention, and here we can identify the theoretical origins of pendulums. Far from appearing abruptly or being exclusively tied to modern science, the pendulum has deeper theoretical roots that can be traced back to medieval debates on the motion of mechanical devices. Thinkers associated with the scholastic tradition and the intellectual environments of the Renaissance began to recognize in oscillatory motion a regularity worthy of analysis, even though this regularity was not yet fully mathematized or understood in its physical foundations.

This article aims to examine precisely this historical moment, investigating the process by which the pendulum ceased to be a marginal instrument and began to be incorporated, albeit incipiently, into the field of investigation of the emerging new science. Furthermore, the study is dedicated to the analysis of the invention of the pulsilogium, considered, as far as is known, the first scientific instrument to deliberately employ a pendular system. More than a mere technical artifact, the pulsilogium will be interpreted as a link between theory and practice. We will explain how the pulsilogium was invented and describe the theoretical work being developed at the dawn of modern science to describe the movement of pendulums.

2. The History of Pendulums

It is remarkable that the pendulum took so long to be incorporated into scientific knowledge. According to [1], despite its seemingly simple nature, the pendulum does not appear in Western thought before the mid-14th century. At least, there is no written evidence to suggest otherwise. As far as is known, there is no mention of pendulums in the Greek tradition, since no classical scientific texts, whether Aristotelian, Platonic, or Alexandrian, address pendular motion. As [1] tells us, one would expect that figures of the stature of Aristotle or Archimedes might well have recognized at least some of the peculiar properties of the pendulum. There is, however, no evidence that they, or any of their contemporaries, did so. In the Eastern tradition (with the exception of Arab philosophers), there are likewise no traces of theoretical studies involving pendulums, only some indications of practical and indirect applications involving them.

> If not in the West, then perhaps in China or in the Islamic world did scholars and technicians find in the pendulum a subject for speculation and application? Once again, the answer is largely negative, with two minor caveats. [1, p. 441]

Although no evidence of theoretical studies has been found, this does not mean that ancient or medieval peoples did not use pendulums in a practical way in their everyday lives. Historically, pendulums have been used since antiquity in ancient cultures. They were of great importance as components of mythological and religious rituals, as well as tools for divination, fortune-telling, and even hypnotic practices. There are records of amulets consisting of small stones attached to the ends of cords, which may be considered among the earliest pendulums. In most cases, early pendulums were simple devices, often consisting of a weight suspended from a cord or chain, and these instruments served a variety of functions in certain religious rituals [2]. In many ancient cultures, it was believed that the pendulum functioned as a bridge between the physical and spiritual worlds. Its gentle, rhythmic motion was thought to be influenced by invisible forces, providing answers from the divine or the supernatural.

This practice, known as *pendular dowsing*, involved interpreting the direction, speed, and pattern of the pendulum's swing in order to obtain guidance, uncover hidden truths, or make decisions. The Egyptians, for example, were known to use pendulums in their religious rites and ceremonies, as well as pendular amulets. They believed that the motion of the pendulum could reveal divine messages or aid in communication with the gods. Similarly, in Ancient China, pendulums were used for *geomancy*, a form of divination that deciphers markings on the ground or patterns created by handfuls of stones or sand that are cast. The pendulum was employed to determine the flow of chi (vital energy) and to make decisions regarding burial sites, the placement of temples, and other important spatial arrangements, in accordance with the principles of *Feng Shui* [2].

Therefore, historically speaking, pendulums have been known to humankind since antiquity; however, there were no theoretical descriptions associated with such objects, and their scientific use was limited or almost nonexistent. One of the earliest known scientific uses of the pendulum was its application in a first-century AD Chinese seismograph (Figure 1). This was a highly innovative device for its time, created by the Chinese scientist of the Han dynasty, Zhang Heng (78–139 AD). The use of pendulums in instruments for earthquake detection is still practiced today. In Heng's device, the function of the pendulum was to move in response to an earthquake, activating a series of levers after being disturbed by the tremor. In this process, the instrument triggered a mechanism that released a small sphere, which fell from the device into a kind of urn positioned below it, featuring eight openings. Each of these openings corresponded to one of the cardinal directions, thereby indicating the direction of the earthquake [3]. Regarding this instrument,

Figure 1: Chinese seismograph invented by the scientist Zhang Heng (78–139 AD), the cylindrical rod-shaped pendulum inside oscillates during an earthquake [4].

> In China, the only suitable candidate for a pendulum device might be the "earthquake weather vane," invented in 132 AD by Chang Heng, Astronomer Royal at the Imperial Office of Astronomy and the Calendar in Peking. Chang Heng's instrument was designed to indicate the occurrence of small earthquakes (. . .). Chang Heng's machine is an excellent example of Chinese ingenuity and employs an element that we might loosely call a pendulum. [. . .] Although it was used successfully in China for a long period of time, knowledge of its mechanical principles seems to have disappeared sometime after the sixth century; later writers knew of it only by reputation. [. . .] There is no evidence that any scientific scholar, Chinese or Western, recognized in the instrument any principles of dynamics [3, p. 70].

This device found in China may be considered the first documented use of pendulums; however, other discoveries by different peoples who employed pendulums in the ancient world may have existed. It is remarkable, given Greek creativity, that nothing concerning pendulums appears in the mechanical works of Archimedes, not even in a practical sense, or in the writings of Heron of Alexandria (10–80 AD), the great mechanician, among other mechanical philosophers of Ancient Greece. In the Middle Ages, there is some evidence that the isochronism of pendulums had already been studied by the Arab astronomer Ibn Yunus (950–1009), but most scholars believe that this knowledge of the Arab philosopher was unknown in Europe and also to Galileo.

We find the use of pendulums in more sophisticated mechanisms in Western Europe, and already in the Renaissance there were large pendulums that were used as a source of energy for mechanical machines with alternating motion such as saws, bellows and pumps [1]. On this subject, [1] says that the historical sources that support the evidence of the pendulum by this Islamic philosopher simply do not exist, and he goes further stating that there is no scientific use of pendulums before the modern period in the Renaissance, however, we believe that pendulums were used in ancient machines in the Middle Ages before the Renaissance, however, without any scientific basis, only as an unconscious use of a device capable of producing movements and generating potential energy to drive the gears of the machines,

> Turning to Islam, we find a persistent myth that the tenth-century astronomer Ibn Yunus employed the pendulum as a time-measuring device in his observations. Numerous popular histories of astronomy credit him not only with the first use of the pendulum, but by implication with some understanding of pendulum isochrony. Such claims turn out to be unfounded in fact and deserve to be set aside. Ibn Yunus's false reputation in this regard does not arise from any claims he made, but from Edward Bernard's misinterpretation of some diagrams in Arabic manuscripts at Oxford. [. . .] No ancient machine appears to have been designed to make use of any property of the pendulum, although some ancient devices exhibited pendulum motion as an accidental feature of their operation. Thus not only did the isochronism of the pendulum remain unknown before the age of Galileo, but its very existence may be considered unknown before the age of Dante" [1, p. 443].

In medieval mechanics, Aristotelian physics had a significant influence, which can be said with some certainty according to [5] that there is no reference in the entire corpus of Aristotle's works to pendulums or any object that resembles it, similarly, pendulums are not mentioned in theoretical texts on mechanics until the second half of the 14th century [5], a direct reference to pendulums can be found in the work of the late medieval thinker Nicole Oresme (1325–1382), in the book *Le livre du ciel et du monde*, when explaining the pendulum, he compares its movement with the movement of a stone, and at this point he makes a comparison using his famous thought experiment, a stone falling into a hole, cutting the entire diameter of the Earth, passes through the center of the Earth and then changes direction and begins to fall towards the center again, thus exhibiting an oscillatory movement. It is not known how pendulums became the object of curiosity of European philosophers, however, as [5] tells us, this explicit reference to pendulums by Oresme seems to indicate that pendulums were not really new to theoretical reflection in the early modern period; it may be that they had already been known to European philosophers for much longer.

> [. . .] For if an opening were made from here to the center of the Earth and beyond, and a heavy object were to fall through that opening or hole, upon reaching the center it would pass through it and begin to rise

> by virtue of this accidental and acquired property; then it would fall again, and they would go back and forth several times, just as we can observe in the case of a heavy object suspended from a beam by a long cord [pendulum]. [6, p. 145].

It is indeed true that this tunnel experiment is not properly due to Oresme, but rather to his master Jean Buridan (1301–1358), who was the first to propose such an experiment as an attempt to consolidate his theory of impetus[1]. Buridan's analysis of the tunnel thought experiment represents one of the most fertile moments of late fourteenth-century scholasticism. This imaginary experiment envisaged that if a cannonball were to fall into a tunnel passing straight through the center of the Earth, it would go beyond the center and rise to the opposite surface, reaching the same height from which it fell on the other side. The justification is that, from the center onward, the body is driven upward by the impetus gravitationally generated and continuously accumulated during its fall toward the center. In doing so, Buridan not only challenges Aristotle's teleological physics, but also establishes what we might call the first dynamic model of harmonic oscillation in the history of science.

This thought experiment was then applied by Buridan's followers to the dynamical explanation of an oscillatory motion in the real world, namely that of the pendulum. The transition from 'Buridan's tunnel' to the 'real pendulum' constitutes a development of the Parisian School, led by Buridan but significantly expanded by Nicole Oresme and other scholastic philosophers. A refinement of this tunnel experiment is the association made with the pendulum by imagining it attached to the end of a cosmologically long cord suspended from the vault of the fixed stars centered on the Earth, by means of which the relatively short arc of its path through the enormously distant Earth was, in effect, practically a straight line along the tunnel [9].

Certainly, such a line of reasoning concerning the motion of a pendulum would have been inconceivable to orthodox Aristotelians, who held that bodies tend toward rest only when they reach their natural place; thus, a pendulum would never be at rest, since the cord did not allow it to reach that place. As Thomas Kuhn remarked, orthodox Aristotelians could only view the motion of the pendulum as a dynamical anomaly, as something inexplicably 'falling to rest with difficulty' [10]. Buridan's new theory of impetus, however, introduced new concepts that could explain the motion of this object more satisfactorily, for in fact the pendulum would not fall with difficulty, but rather in repeated periodic cycles, involving a natural motion of falling downward and a violent motion upward. This was the most sophisticated theory for explaining the motion of the pendulum in the mid-fourteenth and fifteenth centuries; nevertheless, this theory influenced even Galileo almost two centuries later, since the Italian physicist, in several places in his work, drew upon this theory of the dynamics of impetus to explain pendular motion.

The first substantial theoretical reflections on the pendulum that could legitimately be seen as reflections on the pendulum as a challenging object are obviously Leonardo's reflections on the subject [5], no other scholar of this period of the late Middle Ages and early Renaissance made a more in-depth study of pendulums than Leonardo da Vinci (1452–1519). In the *Madrid Codex* [11], Leonardo da Vinci compares the movement of a pendulum with that of a projectile, in this period, there was great difficulty for natural philosophers in explaining the movement of projectiles, especially regarding the Aristotelian problem of projectile throwing and the doctrine of *antiperistasis*[2].

Leonardo da Vinci trying to find a theoretical explanation for the fact that in the case of the pendulum movement the violent upward part of the movement is shorter than the downward part [5, 11], then we can see an evident effort by Leonardo da Vinci in the description of the pendulum movement, which would not be an easy task even at this stage of mechanics, but, as [5, p. 228] points out, the pendulum would only become a challenging object for rigorous theoretical study at the beginning of the modern era. No evident effort was seen in the theoretical study of pendulums before Leonardo da Vinci, and as for Oresme, from what is found in his

[1] Aristotle postulated that the motion of a projectile depended on the continuous action of the medium, since 'everything that moves is moved by something' (*omne quod movetur ab alio movetur*). It was primarily in the 14th century that scholastics such as Jean Buridan (1300–1358) and Nicole Oresme (1320–1382) proposed the theory of impetus as an alternative to the Aristotelian view to explain violent motion without the need to resort to an external agent. In the theory of impetus, the body does not depend on the medium as the agent responsible for the continuity of motion, but rather on the quantity of matter of the body itself [7]. The introduction of the concept of impetus subverted Aristotelian logic by internalizing the cause of motion within the object itself: 'when setting a body in motion, the motor impresses in it a certain impetus, a force capable of moving it in the direction in which the motor started it' [8].

[2] The doctrine of antiperistasis (from the Greek *αντιπερὶσταση*), which basically means anti = against, and peristasis = surrounding, has its origin in a problem of Aristotelian physics. According to this, violent motion is only possible through a mover (efficient cause) that drives a body against its natural place; it is a necessary condition that the mover and the moved remain in continuous contact. Here a problem arises: when a stone is thrown, what keeps it in motion, given that once it is cast it loses contact with the mover? To solve this problem, Aristotle proposes that there must exist some other cause (mover) that moves the stone in its upward motion, for, according to him, 'everything that is moved must be moved by something' [7]. When it is thrown, at the moment of its launch, part of the air is set in motion together with the moved body [the stone]; after the action of the initial moving agent, the air becomes the efficient cause or the moving agent that moves the stone, because the air has been pushed with such force that it pushes the body, trying to prevent a vacuum from forming. This doctrine of Aristotle's theory of motion came to be called, mainly by his commentators, antiperistasis [7].

work his mention of pendulums served only as a resource to support his arguments about the movement inside the Earth, but there is no interest in him in understanding the principles of pendulums as independent objects in themselves.

Da Vinci can be considered the first to recognize the value of the pendulum as a device for time measurement, as he states: '*Time, by its very nature, is continuous, but to measure it, we need something that divides it into equal parts. The percussion of weights that rise and fall [the pendulum] is the master of equality in motion*' [9]. Leonardo frequently used terms such as 'oscillating counterweight' or 'percussion of weights' to refer to what we now call a pendulum.

Studies involving such instruments can be found in the works of several scholars from the late Middle Ages and the early Renaissance. Texts addressing pendulums appear in the writings of Nicole Oresme (1320–1382), Jean Buridan (1301–1358), Giovanni Marliani (15th century), Leonardo da Vinci (1452–1519), and Gerolamo Cardano (1501–1576) [1, 6]. Each of these scholars noted that the primary application of this instrument was in mechanical devices, most notably Leonardo da Vinci, who was a highly skilled designer of mechanical apparatuses, in some of which the use of pendulum mechanisms can be identified [9].

We can say that pendulums gained greater notoriety in the 17th century, it is in this period that we will see applications and theories about pendulums appear that had never occurred until then, it will be then in 1602 that the device called pulsilogium appears, there is some controversy about the invention of this instrument, most historians believe that this invention is due to the work of Sanctorius [12]. However, it is also speculated, as stated by [12], that in addition to Sanctorius, there are at least two other potential candidates for its invention: Paolo Sarpi (1552–1623) and Galileo Galilei (1564–1642), each of whom had their rights to the invention of the device claimed by third parties. We have already commented on the fact that Galileo was not the likely inventor of this instrument, the pulsilogium, and we will bring some arguments about this.

3. The Controversy Surrounding the Primacy of the Invention of the Scientific Pendulum

The pulsilogium is considered the first precision instrument in the history of medicine used to measure heart rate. Most historical sources attribute the discovery of this instrument to Santorio Sanctorius (1561–1636), who was a professor of medicine at the University of Padua. Sanctorius invented the pulsilogium, a simple pendulum of standard length designed to measure the pulse of patients in hospitals. Apparently, the first application of the pendulum as a timekeeping device was in medicine, to determine the heart rate of sick patients; the pendulum was used to time pulse beats [2]. The pulsilogium, first mentioned in 1602 by a colleague of Santorio's in Padua, was a source of inspiration for Galileo and sparked an entire trajectory of pendulum experiments in seventeenth-century Europe [12].

> The emergence of modern science in the 16th and 17th centuries saw medicine as an important field of development, thanks especially to the work of Santorio Santori (1561–1636). Best known for his contribution to the study of metabolism, Santorio was a pioneer in the use of quantification and developed several types of instruments, among which was a device called a pulsilogium that represents the first precision instrument in the history of medicine [12, p. 1].

The first written mention of Sanctorius' *pulsilogium* appears in the book titled *Methodi vitandorum errorum omnium qui in arte medica contingente* (Methods for Avoiding All Errors That Occur in the Medical Art), published in 1603, but we also find some mention of the instrument in another book by Sanctorius, *Commentaria in primam Fen primi libri Canonis Avicennae* (Commentaries on the First Book of the First Canon of Avicenna), from 1625, and in this book we find some comments by the Venetian physician on the *pulsilogium.* In the excerpt below, Sanctorius explains the purpose of the device,

> For the happiness of memory and for the exact knowledge of the pulses, of their equality or inequality, we invented the pulsilogium, in which the movement and rest of the artery can be measured and retained precisely in the mind for comparison with past pulses. [...] With this instrument we can measure the movement and rest of the pulse... and thus we can know on which day and at what hour the pulse deviated from its natural state. [...] In this pulsilogium, we observe the ratio and proportion of the pulse's movement in relation to the movement of the pendulum; and thus we can distinguish between a large, small, fast, slow, rare, and frequent pulse. For the pulsilogium is an instrument in the manner of a plumb line, whose cord length indicates the frequency of the movement [13, p. 467–468].

In another passage, Sanctorius explains the construction of the instrument and its functioning, as we can see below,

> The instrument consists of a cord to which a lead weight is attached. To determine the frequency of the pulse, we adjust the weight so that its movement corresponds to the movement of the artery. Once this is done,

> if we wish to know again [on another occasion] whether the pulse has become faster or slower, we move the weight up or down until the movement of the weight corresponds to the pulse; then, from the length of the cord, a very precise estimate of the frequency or rarity of the pulse can be obtained. On the same instrument, there are also marked degrees [a graduated scale], so that the movement of the past pulse can be compared with the movement of the present pulse; something that was previously impossible for physicians [13, p. 449].

Describing the instrument created by Sactorius is an important point, since it represents an element of great value in the process of transition between Aristotelian physics and the new science of Galileo, as says,

> "The results are possibly of some importance in the history of science, since, contrary to all previous scholars, we can now prove that the pulsilogium represented a moment of transition and departure from late Aristotelian physics towards Galilean mechanics and that, despite the latter's discoveries, it continued to be used not to obtain an absolute measurement of the pulse rate, but to record its latitude" [12, p. 1].

Paolo Sarpi (Figure 2), an Italian polymath who stood out in his time for his broad intellectual interests, was an astronomer, anatomist, theologian, physicist, historian, and a member of the Order of the Servants of Mary (*Ordo Servorum Mariae*). In the field of physics, his work focused mainly on studies of the anatomy of vision and the eye. He was also interested in the controversy generated by the publication of Copernicus's work, *De revolutionibus orbium coelestium*, and exchanged letters with Galileo on the subject. Sarpi was also a scholar with many connections in the academic world.

It is certain that Sarpi heard about the telescope in November 1608, perhaps before Galileo. Sarpi was not merely a monk; he was the Consultore (legal and scientific advisor) of the Republic of Venice and had the official task of evaluating new technologies. In August 1609, a foreigner (probably a Dutchman or an intermediary) arrived in Venice attempting to sell a telescope to the Senate. Sarpi, in his official capacity, reported the following about the instrument: "*A spyglass has arrived that makes distant objects visible. I greatly admire it for the beauty of its invention and its craftsmanship, but I consider it useless for military purposes, whether on land or at sea*" 14.

In 1609, the Republic of Venice sought the approval of a telescope for military purposes. Sarpi knew that Galileo was working on his own model of the spyglass, and he managed to have the foreign model rejected, advising the Venetian government not to purchase that initial version. While holding off foreign buyers, Sarpi wrote to Galileo (who was in Padua, then a Venetian territory) encouraging him to build his own version, superior to the Dutch one. Galileo soon gained fame as the inventor of the first commercial telescope prototype throughout the Italian peninsula. Shortly thereafter, Sarpi also created his own prototype, and, some time later, a controversy arose over who had been the first inventor of the instrument.

Figure 2: Paolo Sarpi (1552–1623) was an Italian Servite friar and Catholic priest who was a notable historian, scientist, canon lawyer, polymath and statesman. Sarpi was also an experimental scientist, a proponent of the Copernican system, a friend and patron of Galileo Galilei [17].

As for the pulsilogium, its attribution to Sarpi is based entirely on what Fulgenzio Micanzio (1570–1654) states in his 1646 biography *Vita del padre Paolo*, in which he claims that not only two types of pulsilogia, but also the thermometer and the telescope, were invented by the Venetian friar. As we know today, the telescope was not Sarpi's invention, and, with regard to the thermometer, there is a controversy involving Paolo Sarpi, Galileo, and also Sanctorius. With the exception of a few notes from his collection of thoughts (Pensieri, no. 547), Sarpi's scientific studies on the pendulum have not been preserved, and the surviving testimonies do not allow us to assess with historical precision what Sarpi's contributions to the evolution of this instrument were [12].

Fulgenzio Micanzio, who was Sarpi's right-hand man and successor, held great admiration for his mentor and, in his work *Vita del padre Paolo*, sought to ensure that posterity would recognize Sarpi as the true genius behind several inventions that he believed had been unjustly attributed to Galileo or to Sanctorius. For this reason, he claimed in his book on Sarpi's life that the inventions of the telescope, the pulsilogium, and the thermometer should be credited to Sarpi. We do not know whether Micanzio was right in these claims; however, he reports that Sarpi carried out studies on the pulsilogium and on the properties of pendulums [15].

According to Micanzio, Sarpi developed two distinct methods for using the pendulum in medicine: (i) a Variable-Length (Graduated) model, which consisted of a string with a weight at the end. Sarpi is said to have created a linear scale behind the string (or markings on the cord itself), so that the physician could record a specific number for each patient, allowing the pulse to be compared quantitatively from one day to the next; (ii) the "Beat-Comparison" model, in which, instead of adjusting the string for each patient, the pendulum was used as a metronome to categorize the type of pulse, something very useful in the medicine of the time, which was strongly based on humoral theory and on the musical rhythms of the body [15].

In his book *Vita del Padre Paolo*, Micanzio states that many of Sarpi's contemporaries, after conversing with him, became aware of his inventions and then went on to refine the instrument and present it as if it were their own invention. Possibly, Micanzio was referring to Sanctorius. He writes the following,

> He [Sarpi] also invented the use of the pendulum in medicine, and of this he made two types: one in which the string is lengthened or shortened until its oscillations coincide with the beating of the pulse; the other, with a string of fixed length, in which one observes how many oscillations occur in the time of a given number of pulse beats. [. . .] Many who conversed with him [Sarpi], after learning of his inventions, published them as if they were their own; but he, in his modesty, never concerned himself with this [15, p. 78–80].

In the case of Galileo, historians rely primarily on what Vincenzo Viviani (1622–1703), Galileo's last and most faithful disciple, wrote in his biography of his master, entitled *Racconto istorico della vita di Galileo* [16], dated 1654. Viviani writes that around 1582–83 Galileo invented an instrument to measure the pulse while he was still a medical student in Pisa, and that he later described his invention to physicians. This account, however, is unlikely, since Galileo was rather impulsive and, when he made a discovery, rarely waited long to publicize it, whether to secure his priority or simply to gain recognition among his peers. At this early stage of his career, he was even more concerned with proving his worth in order to obtain a chair; it is therefore probable that, had he made such a discovery at that time, he would have made it public. Unlike in the case of Sarpi, however, the attribution to Galileo can be supported by other evidence, in particular by a letter sent to Guidobaldo Del Monte (1545–1607) on 29 November 1602, in which Galileo describes certain aspects of the motion of the pendulum, although it contains no mention of the pulsilogium, as far as is known.

Although the surviving letter is not the original, but rather a second-hand copy of another copy of Galileo's original letter, there is no reason to doubt its authenticity or its date. This letter has been studied by many historians for different purposes. Although it clearly concerns some form of experimentation with the pendulum, it does not imply any practical application, nor does it provide any mathematical proof of pendular motion; most importantly, it does not prove that Galileo invented the pulsilogium. It does, however, indicate that Galileo was studying the theoretical properties of the pendulum prior to 1602. Galileo merely refers to certain experiments he carried out (*experienze*) and to a plausible mechanical explanation (*senza trasgredire i termini della meccanica*) [12].

The letter itself is therefore not historical evidence in support of the commonly suggested idea that Galileo may have been the inventor of the pulsilogium. In this letter to Guidobaldo del Monte (1545–1607), Galileo discusses his ideas on the principles of pendulums. As already noted, Galileo himself makes no claim to any inventions or practical applications resulting from his work on the pendulum, which may indicate that he did not invent the instrument. Had he in fact developed such inventions or applications, he would have had no reason to conceal them from a friend such as Guidobaldo, since describing them would have strengthened his argument. We shall examine some passages from this correspondence between Galileo and Guidobaldo del Monte later on.

4. The Confirmation of Sanctorius as the Inventor of the Pulsilogium

Santorio Sanctorius (1561–1636) was an Italian physician, physiologist, and experimentalist. Although he was not Italian by birth, he spent most of his life in the Kingdom of Italy. He was a professor at the University of Padua from 1611 to 1624. Sanctorius's work focused on medicine and its applications. It is not known how Sanctorius became acquainted with the pendulum and its principles; however, as an innovator and a notably curious experimenter, he was probably part of a circle of experimentalists typical of the Italian Renaissance. Sanctorius conducted experiments on respiration, weight, and temperature, and he also studied the medical applications of these experiments.

His interest in inventing the *pulsilogium* may have stemmed from his desire to benefit from scientific knowledge and experimental practice in order to advance medicine. His work was remarkable for its time, given the lack of scientific instruments for measuring basic clinical data; medical practice, then, was largely focused on healing based on the doctrines of Hippocrates (460–377 BC) and Galen of Pergamon (129–216 AD). Another reliable contemporary testimony concerning an instrument called the pulsilogium appears in the treatise *De pulsibus libri duo*, published in 1602 by the physician Eustachio Rudio of Belluno (1548–1612), a friend and colleague of Sanctorius at the College of Physicians of Venice, as well as professor of practical medicine at Padua. The fact that Rudio was a friend of Galileo and a professor at the same university where Galileo taught may have facilitated the dissemination of the instrument; through exchanges between Rudio and Galileo, he may have introduced the *pulsilogium* to him. However, the fact that Rudio attributed priority of the discovery to Sanctorius constitutes the strongest evidence we have for establishing the latter's priority as the inventor of the instrument, apart from Sanctorius's own book, *Methodi Medica Contingente*. The following excerpt presents Rudio's words on the pulsilogium in his treatise *De pulsibus libri duo*,

> I just want you to know that in our era (nostra aetate) an instrument – which one might call a pulsilogium – has been invented to discern the rapidity and slowness of the pulse. Its author is Santorio Santori, a physician, a philosopher, and a man gifted with all kinds of learning. This is clearly a wonderful event, and represents a sure proof of the perspicacity and sharpness of mind of such a man. Thanks to this device, in fact, we can measure exactly the movement and rest of the pulse, and thus the rapidity and slowness of the present pulse can be compared with that of former days with absolute precision [12, p. 58].

Regarding the precise publication date of this book, there is little doubt about its authenticity, and it is quite likely that it was published well before the end of 1602. Thus, the hypothesis that Galileo, as a professor in Padua at the time, may have heard rumors about Sanctorius's invention of the pulsilogium and, perhaps influenced by news of the new device, the Florentine physicist might have become interested in investigating pendulums or perhaps had already done so is also quite plausible. Certainly, there is some uncertainty about the period in which Galileo began his research on the pendulum. It is not known for sure whether he started before or after 1602. In his letter to Guidobaldo del Monte, there are some indications that Galileo had begun his research on the pendulum before 1602. Nevertheless, in any case, we can conclude that by the time Galileo wrote to Guidobaldo, the pulsilogium was already known to Galileo's colleagues in Padua. This point, although not fully supported by historical evidence, leads us to consider another possibility. As he states [12],

> There is also the possibility that, since Galileo's interest in studying the pendulum did not begin seriously before 1602, his interest was sparked by Santorio's discovery and Rudio's announcement, a hypothesis that is reinforced by the fact that Galileo participated as a subject in Santorio's metabolic experiments. This does not imply that Galileo relied on Santorio's studies for his discoveries, it only attests that the first historical record of an instrument using a pendulum recognizes Santorio as its inventor and that, as we will show in the following paragraphs, he was working, together with Galileo and Sarpi, on a legacy of shared ideas [12, p. 58].

After the publication of Rudio's book in 1602, Sanctorius himself published a description of his instrument in the same year. From that point onward, Galileo began to study the physical properties of pendulums. He initiated research on isochronism, and his descriptions of the results of this research would only later be included in his book *Discourses and Mathematical Demonstrations Relating to Two New Sciences*, which was published in 1638 [18].

> After Rudio's announcement (1602) and Santorio's first description (1602/3), many other physicians and scientists began to be attracted by the possibilities opened up by the pulsilogium. Some of these records are particularly interesting. In 1611, Caspar Bartholin the Elder (1585–1629) published a small book collecting a series of opinions on medical and philosophical problems from all over Europe. One of them is a report by the Venetian physician Antonio Fabri, who confirms the invention of the pulsilogium by Santorio and had the opportunity to witness its application to medical practice. Ten years later (1621), Peter Lauremberg (1589–1635), a physician at the University of Rostok in Germany, was able to replicate and successfully apply the pulsilogium to explore the usually imperceptible differences in pulse rate (omnigena pulsuum discrimina). He says he was told that Santorio was the inventor of such an instrument (qualia a Sanctorio excogitata accepimus) [12, p. 59].

5. The Theorization of the Pendulums in the Works of Benedette and Sanctorius

What is interesting about Sanctorius is that he was not only pleased with the invention itself, but also devoted himself to understanding the physics behind it. In Sanctorius's earliest description (1603), he states that the *pulsilogium* is "*an instrument capable of showing all differences in equal motions*" [19] that is, a mechanical device capable of producing equal intervals of time, which can be measured by calculation through equal motions. In one of his later explanations, from both 1612 and 1625, Sanctorius (Figure 3) notes that the mechanism regulating his *pulsilogium* is the pendulum, which is how equal intervals of time can be measured; therefore, it is not difficult to regulate it using a person's pulse. Sanctorius certainly possessed knowledge of mechanics, and this is revealed in a passage in which he seeks to clarify his understanding of the dynamics of pendular motion. As he says [12], "It is quite remarkable that, by pushing the ball a little more strongly or more gently, its frequency or speed is not altered, because when the distance is reduced, the force is correspondingly diminished (*tantum amittitur de spacio quantum enim remittitur de violentia*)".

Figure 3: Santorio Santori was an Italian physiologist, physician, and professor who introduced the quantitative approach to medical science and is considered the father of experimental physiology. He is also known as the inventor of several medical devices, including the pulsiologium [20].

This passage reveals that Sanctorius possessed a reasonable understanding of the variations of dynamic quantities in the oscillatory motion of the pendulum. In his explanation, he assumes that force and the distance traveled are proportional, since, if the distance traveled increases, the force increases, and if the distance is reduced, the force correspondingly decreases. He therefore claims that there is a proportional relationship between them. Likewise, when he states that the motion of the pendulum does not alter its frequency or its speed, given that frequency is the number of oscillations within a given interval of time and that one oscillation represents a certain displacement, distance and speed must therefore be directly proportional.

Thus, Sanctorius describes how the force applied to a ball does not affect its frequency or its speed, regardless of the distance traveled by the ball. He tells us that, when the space is reduced, the force diminishes proportionally, expressing the idea that the greater the distance traveled, the greater the force, or "violentia" This constitutes an attempt to address the relationship between distance and speed, suggesting that these two variables are directly related in a proportional manner. Moreover, Sanctorius appears to have had a vague notion of the law of isochronism, most likely independently of Galileo. As he states,

> In the pulsilogium, in fact, we observe two things. One is the weight suspended by a thread; if this is set in motion, we observe in it that as much space is lost as the violence is diminished. For this reason it happens that, whether it is moved by a greater or a lesser force (violence), it always moves in the same time and completes similar and equal motions in the same period [19, p. 219].

Some scholars have speculated that this passage by Sanctorius constitutes an implicit statement of the principle of pendulum isochronism, such as Raffaello Caverni (1837–1900), who claimed that in this passage Santorio presupposed the absolute isochronism of the pendulum [12]. However, there is no evidence that he possessed any understanding of this principle. Galileo himself took years to arrive at the law of isochronism before he was able to articulate the principle. Santorio's explanation is connected to the development of the late medieval theory of the "latitude of forms" and also to mechanical theory through the idea of "violentia" (force), which can be understood as the intensity of motion. Moreover, this passage by Sanctorius suggests that this explanation is also related to the Renaissance controversy over equilibrium, particularly to the discussion of how weights behave on a balance; this question of equilibrium greatly influenced early modern mechanics.

The Venetian mathematician Giambattista Benedetti (1530–1590) was involved in this controversy. Benedetti was born in Venice and is known for his work in physics, where he anticipated Galileo's work on the free fall of bodies. Having made significant progress in this field, he likely influenced Galileo. In 1554, he published the work *Demonstratio proportionum motuum localium*, in which he outlines several aspects of his theory. The fact is that at that time the entire science of motion was undergoing revisions. Philosophers were having difficulty reconciling Aristotelian mechanics with the new phenomena that were emerging. We must therefore understand that Sanctorius' ideas were involved in this context, especially regarding the Renaissance dispute over equilibrium, a concept that still caused difficulties for Renaissance philosophers.

According to [12], the controversy over equilibrium revolved around the behavior of weights that are deviated from their equilibrium position on the equal arms of a balance, and this issue also involved the movement of the pendulum. The equilibrium controversy in Renaissance physics involved the analysis of how weights behave in a system of unequal weights on a balance (Figure 4). On a balance with two arms of equal length, if weights are placed on both sides and one of the weights is moved from its equilibrium position, the balance will oscillate until the weights balance again. The focus of this controversy was on the behavior of these weights when moved from their equilibrium position. Benedetti was one of the leading scholars of his time to engage with this problem of equilibrium; he was not particularly concerned with the consequences of equilibrium theory regarding the pendulum, yet he possessed some knowledge of the pendulum, despite never having published any detailed study on the subject.

Figure 4: An illustration of the Roman balance (or *statera*), a common instrument used for the study of equilibrium by Renaissance philosophers [12, p. 62].

For Renaissance philosophers, the pendulum was regarded as a special case of the balance. It was interpreted as a balance whose axis of rotation was the point where the string was attached. Thus, it would not have seemed strange to Renaissance natural philosophers to relate motion along a circular arc to a balance. Benedetti was one of the first to analyze circular motion and equilibrium. As he stated, "*every heavy body that moves circularly seeks the lowest place, just as occurs with balances; for the motion of the weight along the arc [of the pendulum] is nothing more than a continuous search for the equilibrium provided by the perpendicular line*" [21].

In other words, Benedetti understood that a balance seeks horizontal equilibrium: when it is set in motion and one of its arms is tilted, the weight tends to return to the horizontal equilibrium position. The pendulum, by contrast, seeks vertical equilibrium, which corresponds to the perpendicular line. When the weight is displaced from the vertical, it attempts to return to the center, exactly like the arm of a balance, but oriented vertically [21].

Sanctorius addresses this issue of Renaissance mechanics by relating the pendulum to the balance. He explicitly employs the balance analogy to justify the precision of his pulsilogium, "*we observe in the pendulum the same as in the balance: just as in the balance the equality of weights produces rest, in the pulsilogium the proportion between the length of the string and the 'violence' of the motion produces equality of time*" [13]. Within this renaissance tradition, the suspending string of the pendulum is analogous to the supporting arm of a balance; what changes is the point of support. In the pendulum, the support is located at one end of the string, whereas in the balance the point of equilibrium lies at the center of gravity of the supporting arm, in accordance with the law of the lever. The motion of the pendulum is therefore analogous to that of an unbalanced balance; only the axis of displacement differs.

Both in the pendulum and in the balance, the moment of force increases as the distance from the equilibrium point increases; in other words, the farther a weight moves from the fulcrum, the greater the restoring force or the 'moment' (*violentia*) that tries to bring the system back to equilibrium. This was the position discussed by the physicists of the time. Benedetti, in an attempt to overcome this challenge, showed disagreement with some aspects of Aristotelian physics,

> Giambattista Benedetti (1530–1590), in 1585, stood in open contradiction to certain principles of Aristotelian physics: drawing on Archimedes' De aequi ponderantibus, Benedetti argued that the weight, and consequently the 'moment' of a body on a balance increases proportionally with its distance from the fulcrum. As a result, if one of the two weights is raised and the other is allowed

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> to move freely downward, it will reach the point of rest (that is, the center of gravity) more quickly if it falls from a position farther above the horizontal line and, conversely, more slowly if it falls from a nearer position, regardless of its initial weight. In short, it will acquire greater or lesser moment (*intendit aut remittit violentiam*) according to the distance traveled, so that shorter distances correspond to less force and vice versa, exactly as in Santorio's description [12, p. 61].

This problem, discussed in the context of renaissance science and the early modern period, did not originate at that time; in fact, within Arabic science there were already studies addressing the problem of *gravitas secundum situm* ('positional weight'). It is possible that there was some influence from Arabic writings on European scholars in the late Middle Ages, and the question of equilibrium was also part of the problem.

> This concept of *gravitas secundum situm* ('positional weight') was particularly important in the case of balances with unequal arms (*staterae*), where a smaller weight on the longer arm could counterbalance a larger one on the shorter. Being a case of equilibrium and an application of the principles of balance, the movement was primarily conceived as obeying a circular motion [12, p. 61].

The problem of *gravitas secundum situm* (literally, 'weight according to position' or 'positional weight') was a widely discussed issue in ancient and medieval science, especially within the Arabic tradition. The problem deals with the fact that the effectiveness of a weight does not depend solely on its absolute weight (amount of matter), but also on the position it occupies in a mechanical system, such as a balance or a lever. In Aristotelian physics, weight (*gravitas*) was associated with the natural movement toward the center of the world. When a weight is on a balance, it cannot follow this natural movement directly; its motion is constrained and occurs along a circular arc. The balance transforms the vertical movement of the weight into angular movement around the fulcrum, in a manner very similar to a pendulum, because the natural tendency of the weight would be to move in a straight line toward its natural place.

The pendular system prevents the body from following its rectilinear motion; instead, the weight acquires an oscillatory circular movement (restricted movement). As Jurgen Renn and Peter Damerow state, the authors point out that the physics of the time attempted to understand the curve described by the pendulum by approximating it to a vertical free fall; geometrically, at the beginning of the motion, the circular trajectory and the straight line of gravity are so close that they overlap, with this similarity being defined by the angle between the two trajectories [12].

The debates caused by the problem of weight differences on the balance were very important in this period of early modern science, given their ramifications for the theory of pendular motion – a problem that, it is worth noting, was little discussed in the previous century and had quite rudimentary foundations, as we saw in our comments on the ideas of Oresme and Da Vinci in the 14th and 15th centuries regarding pendulums. In a single century, things changed considerably. By the late 16th century, the dynamics of the pendulum were already at a fairly advanced stage. Guidobaldo Del Monte (1545–1607) also conducted studies on the problem of scales and equilibrium.

Guidobaldo was a 16th-century Italian mathematician, philosopher, and astronomer. Born into an aristocratic family, he studied in Padua and, as a young man, spent time in the military. After his service, Guidobaldo returned to his estate in Urbino, where he devoted his time to researching mathematics, mechanics, astronomy, and optics; his contributions to mechanics are particularly notable. Del Monte met the young Galileo and recognized his academic abilities; he supported Galileo before the Grand Duke of Tuscany on several occasions and helped him secure professorships at the Universities of Pisa and Padua.

The two scholars shared the same interests in the study of natural sciences. Of particular relevance to our study is the discussion between del Monte and Galileo regarding the isochronism of pendulums. Apparently, Benedetti's work exerted some influence on Del Monte. Regarding the comparison of the phenomenon of the scale with that of a suspended weight, he states, '*if a weight is suspended by a thread, it will behave as if it were on one of the arms of a scale; the difference is that the center of gravity seeks the perpendicular line of the Earth not to stop, but due to a natural inclination that makes it oscillate around this line*' [22].

In the following century, essentially all problems were either completely or partially resolved. We then encounter the mechanical model of the pendulum, whose primary properties had been discovered, along with an adequate description of pendular motion, thanks to the work of Galileo and other 17th-century natural philosophers. It is within the context of Galileo's letters to Del Monte that we find a more fruitful concern with the physics of the pendulum, and Galileo was not the only one with discoveries to report. Del Monte, for instance, applied these principles to a particular case in which the center of the world is located at the base of the circle described by the balance, a problem that seems to lie at the very foundation of Santorio and Galileo's approach to the pendulum problem [12].

So there is some indication that Sanctorius' work on the study of the pulsilogium originated from his possible involvement in the debate on the problem of balancing weights, and that his inspirations in these discussions may have led him to his conclusions on the principles of pendulums. It is likely that Sanctorius had contact with the work of Benedetti and also of Del Monte, having studied at the University of Padua. As pointed out in [7], the theoretical proximity between the works of Del Monte and Santorio is not merely a coincidence, but finds documentary evidence. This connection was identified in rare copies of the second edition of the Commentaria. It is in this little-known text that the Italian physician makes rare mentions and comments about the pulsilogium, one of the most relevant being where Sanctorius states that '*all pulsilogiums maintain constant proportions between their oscillations, as their frequency increases or decreases according to the greater or lesser arcs of circumference described by the pendulum*' [12].

But both in this work of Sanctorius, *Commentaria in Primam Fen Avicennae*, and in other parts of what survives of his writings on the *pulsilogium*, it is implied that '*in short, then, the question of pendulum motion arises from the equilibrium of weights*' [12]. It is almost certain that, based on the analysis promoted by Sanctorius on pendulum motion, he was immersed in the debate on the balance of weights and, drawing on the considerations of his predecessors, made some analogies with pendulums, from which he drew conclusions such as the one in which he affirms that 'all pulsilogiums maintain constant proportions between their oscillations'.

6. Isaac Beeckman's Study of the Pendulum and the Evolution of the Pulsilogium

Sanctorius's book, *Commentaria in Primam* of 1625, exerted some influence on the thinking of his contemporaries. Perhaps one of the most curious natural philosophers of his time was the Dutchman Isaac Beeckman (1588–1637). He read the book of his Italian colleague and did not confine himself merely to speculation regarding the properties of the pendulum, which Sanctorius discusses in his work in reference to the *pulsilogium*. Beeckman sought to apply to the pendulum the phenomenon of string vibration, starting from the principle that both phenomena shared the same fundamental mechanical nature. For the Dutch thinker, the string of a musical instrument was nothing more than a pendulum operating at high speed. He argued that, just as the pitch of a string remains constant regardless of the force with which it is plucked, the period of oscillation of a pendulum should remain invariable, regardless of the amplitude of the arc traversed, as he states: "*When a string vibrates, indeed, the pitch of the sound remains constant, even though the vibration – that is, the space traversed between two consecutive oscillations – is greater at the beginning than at the end*" [12].

We may note that Beeckman's theory was formulated in an attempt to explain the property of pendulum isochronism. That is, unlike Beeckman or Galileo, Sanctorius was not concerned with proving that the time is the same for large or small arcs. His focus was on scale: he graduated the string of the *pulsilogium* so that physicians could record the exact length of the string as a function of the pulse. Certainly, the principle of pendulum isochronism was what made the instrument useful for measuring the pulse. In Beeckman's case, his interest lay in justifying the property of pendulum isochronism. Although the analogy with string vibration offered a physical explanation for isochronism, it did not resolve the problem; the Dutch physicist sought to prove his intuition about the apparent behavior of the pendulum on the basis of a more solid theoretical mechanism.

Beeckman therefore resorted to the theory of 'positional weight' (*gravitas secundum situm*) in a note on his reading of Sanctorius's book in his diary dated December 1630, in which Beeckman began to investigate the reason why strings vibrate while passing through different spaces in the same period, given the fact that the vibration is greater at the beginning than at the end [12]. His intention was to use mechanical principles to ensure that the same pendulum would traverse unequal distances in equal times, and the solution he found was,

> Let ae then be the rope from which the weight is hanging perpendicularly. Raise the same weight to b; it is clear that, in this position, it has the same tendency to fall as if it were not attached to the rope. Divide b into two equal parts, so that the angle bac is half of the right angle bae. As a result, the force fb, that pulls downward, or that which comes from above and pushes downward, is twice as great at b as at c, since it exerts its pressure only at the angle ach, which is half of abf. Indeed, the particles that press upon the weight c (which, while the weight c is in the middle, tend downward along the vertical line) affect this weight with only half of their force [12, p. 64].

The arc be is twice the arc ce, (see Figure 5); Beeckman believed that the velocity imparted to the weight at point b is twice that acquired at point c, because the pressure of gravity is twice as great. Beeckman, being an atomist, believed that gravity was caused by small particles bombarding objects downward. At b, these particles strike the weight more directly, pushing it downward with full force; at c, since the weight is in a position where the rope has a greater inclination, it receives only half of these 'blows' from such particles and is therefore less strongly driven downward. Unlike his older contemporaries, who claimed that the weight 'desired' the center, Beeckman argued that the weight

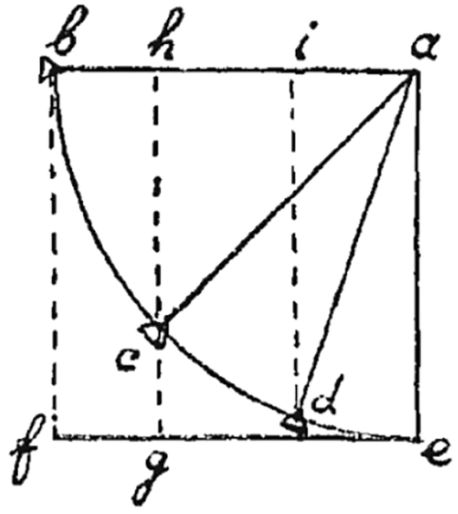

Figure 5: Diagram of a Beeckman pendulum found in his diary, written by him in December 1630; it is on the basis of this diagram that Beeckman attempts to prove isochronism [12, p. 64].

was pushed downward by particles (*Materia Subtilis*), an idea that anticipated the concept of gravity, at a time when Aristotelian theory was being increasingly challenged.

However, as stated in [12], Beeckman admits that this explanation works only under ideal conditions, without air resistance. Furthermore, he believed that bodies of different weights would produce different results with respect to time, that is, the property of isochronism is not independent of the pendulum's weight; in general, under real conditions, the theoretical model proposed by Beeckman for isochronism may not be valid in the same way it was idealized. Despite being a work of great importance, unfortunately these studies by Beeckman were not published and ended up exerting little influence on his contemporaries. In one passage from his writings we also find a section in which Beeckman explicitly expresses himself on the isochronism of pendulums; let us see,

> A ball suspended by a string, if displaced from the vertical, gradually returns to rest; but whether it is moved through a large or a small arc, it returns in nearly the same time. For where it is farther from the vertical, it is there more strongly impelled by gravity, and therefore moves more rapidly; where, however, it is less distant, it is less impelled and moves more slowly. This speed combines with the slowness in such a way that the times of all the returns are equal [23, p. 26].

Regarding the functioning of the *pulsilogium*, Sanctorius, as we have seen, conceived it for medical use. Sanctorius invented many other practical devices: the medical scale (*statera medica*), the anemometer, the clinical thermoscope, and the hygrometer. All of these devices were created by this influential Italian physician with the aim of facilitating the quantitative measurement of biological phenomena, transforming subjective and qualitative clinical observations into numerical, quantitative data. For Santorio, health was the result of a physical balance that could be weighed, measured, and quantified, as he himself stated in his *De Statica Medicina*: "*the physician who does not master quantity cannot cure*" [24]. Thus, his inventions allowed variables that had previously been invisible, such as subtle variations in body temperature or the rhythmic frequency of the pulse, to be recorded objectively. This mechanical and mathematical approach to the human body not only broke with the tradition of the time, but also established the foundations of the experimental method in modern medicine.

Regarding the functioning of the *pulsilogium*, its main purpose was the measurement of a patient's pulse. More precisely, the device allows a comparative measurement of the pulse, expressed as the difference between two or more consecutive measurements [12]. Concerning its operation: the physician held the pendulum and adjusted the length of the string (raising or lowering the weight) until the pendulum's swing was in perfect synchrony with the patient's heartbeat. Santorio used a horizontal rod or a graduated ruler along which the string ran; this ruler was marked with numbered divisions in degrees. When the pendulum's motion was in sync with the heartbeat, the physician would note the position of the marker on the string relative to the fixed scale. If the marker was at the 70 mark, the pulse was recorded as 70 degrees. Thus, according to [12], if on a certain day a patient's pulse is 70 degrees and on the following day it is 65 degrees, Sanctorius recorded that the pulse had decreased by 5 degrees. In this way, each successive measurement provides the difference between pairs of readings.

In general, Sanctorius recorded his measurements in the form of ratios (proportions). If there were no variations in measurements taken at different times, this indicated that the patient's clinical conditions were normal. As stated in [12, p. 67], "*since the frequency of the pulse tends to remain constant under normal conditions, this would give the same reading on the instrument's scale*". If two consecutive measurements of a patient's pulse yielded the same result, Sanctorius recorded them as ratios 1:1, 1:2, 1:3, etc., depending on the outcome. However, if irregular variations occurred (increases or decreases in the pulse), such data were recorded by Sanctorius as comparisons of degrees, for example, 70:65, 65:55, and so on.

Sanctorius explains what his instrument allows him to do: "to observe all the proportions relative to the pulse" (*omnes proportiones observae*); that is, through mathematical proportions, he measured the frequency of the pulse. If there was any irregular variation, it was a sign that the patient had a problem. The term "proportion" (*proportio*) was sometimes used quite literally, as Santorio usually collected the results of his statistical experiments only in terms of mathematical proportions [12]. Johannes Marcus Marci (1595–1667), an influential physician from the Kingdom of Bohemia, also employed the use of the pulsilogium in his medical practice. He not only used it but also improved Sanctorius's original device. See Figure 6, which is an engraving of Marci's *pulsilogium* from 1639, as it became known.

Another scholar who developed an evolution of Sanctorius's original device was the German polymath and Jesuit Athanasius Kircher (1602–1680). While Santorio used a peg[3] to wind the string and alter its length (a simple axle system), Kircher introduced a system of counterweights and pulleys. In other words, Kircher's instrument featured two weights that could be raised or lowered to correspond to increases or decreases in the pulse frequency. This design allowed the pendulum to remain more stable during oscillation, preventing the string from slipping or losing calibration over time, something quite common in Santorio's wooden peg models. See Figure 7.

Kircher's system functioned as a kind of vertical balance. The device consisted of a vertical wooden platform (like a tall ruler) with a graduated scale. At the top, there was a small pulley, through which a string passed, connecting two weights. The pendulum weight was the one that swung freely, while the indicator weight ran along the graduated scale to mark the measurement. To measure a patient's pulse using this tool, the physician placed one hand on the patient's wrist and, with the other hand, pulled or released the string, moving the weights. The aim of this procedure was to find the exact string length that made the pendulum oscillate in perfect rhythm with the patient's heartbeat. If the pulse was fast, the physician shortened the string (moving the indicator weight upward), and if the pulse was slow, he lengthened the string (lowering the weight). Once the pendulum and the heartbeat were in synchrony (beating together), the physician noted where the indicator weight had stopped on the scale, thus determining the pulse. Kircher's philoschronometer of 1665 was certainly a much more precise device than Sanctorius's pulsilogium (Figure 8), whose initial design had been described in 1602. See Figure 9, which shows a replica of Sanctorius's pulsilogium [25].

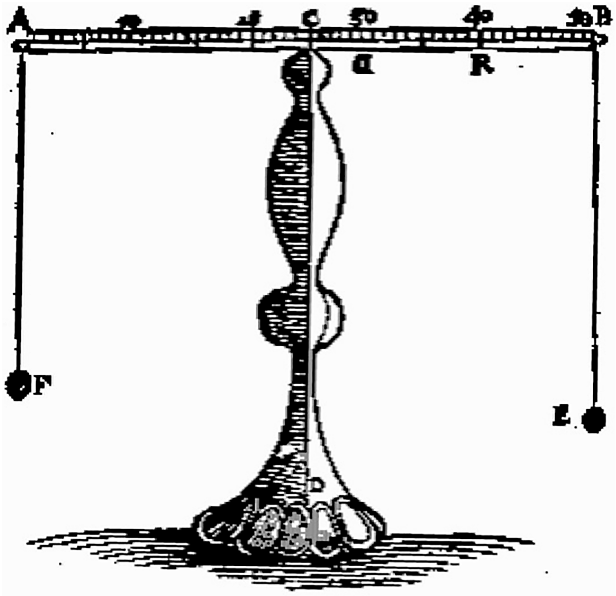

Figure 7: Kircher's philoschronometer was an evolution of Sanctorius's pulsilogium; the design of the device was presented in 1665 [12, p. 64].

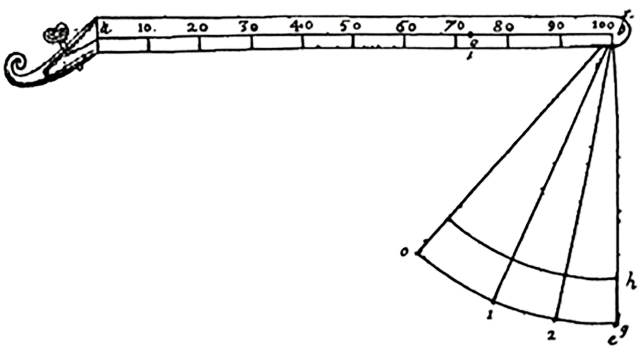

Figure 6: Marci's pulsilogium; this instrument was first presented in his book *De Proportione Motus*, published in 1639 [12, p. 64].

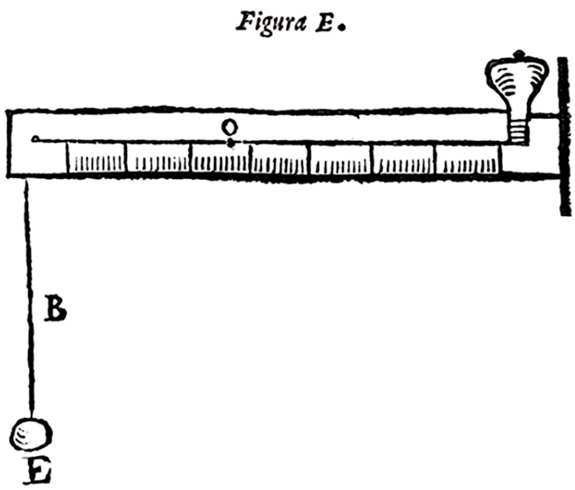

Figure 8: One of the few illustrations of Sanctorius' *pulsilogium* [12, p. 69].

[3] The peg (identical to that of a lute from the period) was located at the top of the instrument. By turning the peg, the physician could wind or unwind the string, changing the distance of the weight. See Figure 8.

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Figure 9: Real replica of the *pulsilogium* [25, p. 3].

7. Final Considerations

From the discussion presented in the sections above, we have seen the historical development and conceptual evolution of the pendulum, not only from a theoretical perspective but also from a practical standpoint, with the creation of the pulsilogium. From what we have observed, it was not the invention of the pulsilogium that gave rise to the theoretical study of the pendulum; this object had already been gradually incorporated into the scope of natural philosophy since the 14th century through the pioneering work of Nicole Oresme, Da Vinci, and Jean Buridan, even though these philosophers' references to the new device were occasional and not in-depth. Genuine interest in understanding the physical nature of the device arose only between the 16th and 17th centuries, when philosophers made more significant efforts to comprehend pendular motion, associating it with the problem of *gravitas secundum situm* and with the problem of equilibrium, relating the pendulum to a balance.

The introduction of mathematical techniques in the investigation of pendular motion was already present in the works of philosophers prior to Galileo, as was the case with Giambattista Benedetti and Guidobaldo del Monte; in the case of Santorio Sanctorius, he began working with the pendulum at the same time as Galileo. All of them, even though still strongly tied to the tradition of Aristotelian physics, broke with the established tradition in some respect, proposing new properties in their efforts to explain the phenomenon of the pendulum. Based on the written evidence, Sanctorius was very likely the inventor of the pulsilogium, the first scientific device to make use of the pendulum in its operation; although its application was aimed at medicine, physicists soon realized its usefulness for measuring time. Paolo Sarpi apparently also contributed to the theoretical study of the pendulum at this time; unfortunately, his writings were lost, and nothing can be known about his research.

All of these thinkers preceded Galileo's work, which refutes the notion that he was the one who initiated the study of the pendulum by enunciating the law of isochronism and other properties of the instrument. As we have seen, not even the law of isochronism can be entirely attributed to Galileo, since there are suspicions that Sanctorius also knew this property, perhaps independently of Galileo, unless Galileo shared his ideas with Sanctorius – which would not be unlikely, considering that they were friends and exchanged correspondence on various scientific subjects, possibly even discussing the pendulum in particular.

Furthermore, as we have seen, Isaac Beeckman was also familiar with the law of isochronism of pendulums, most likely independently of Galileo, which further strengthens the argument against the precedence of the Italian scholar regarding the properties of the pendulum. There is some written evidence that Sanctorius was aware of the law of isochronism; for example, when he states, '*all pulsilogiums maintain constant proportions in their oscillations*'. Furthermore, the pulsilogium depended on this law for its operation. Thus, at most, we can assume that he knew the law in a practical sense, and perhaps also in a theoretical one. However, it is, without a doubt, almost certain that Galileo was the first to propose this law in a letter to Guidobaldo del Monte in 1602, and he also made great efforts to attempt to prove it. In any case, the theorization of the pendulum's isochronism can be credited to Galileo.

Galileo's work, due to its importance, depth, and scope, must be studied separately. In any case, our next step will be a more dedicated and detailed investigation of Galileo's work on the pendulum, analyzing how the Florentine physicist described his research, whether through letters or his publications on the subject. We will examine the difficulties Galileo faced in his investigation of these instruments. He can be considered the first physicist to use experimentation to study pendulums, such as through the use of inclined planes.

Appendix: Some Geometric Considerations Regarding the Balance of Weights

Throughout our previous discussions, we commented on Benedetti's work regarding the equilibrium of weights on a scale, a problem which, as we have seen, strongly influenced the Renaissance analysis of the pendulum that preceded Galilean studies on the instrument. In this section, we will address certain aspects of Benedetti's theory of equilibrium in greater depth; such commentary is important due to the association made by physicists of that era between the scale and the pendulum.

The farther a body is from its 'natural center' or point of rest, the greater the 'violence' (the force required) needed to move it; in other words, the farther the body is from its position of equilibrium, the more intense the force, since more '*violentia*' is required to restore it to equilibrium. Sanctorius (and other thinkers of the period) grappled with the idea that the force acting on a moving body depends on the distance traveled, but also that, according to Aristotelian physics, motion and weight are closely tied to the position of the body: 'to understand this point, we must keep in mind that, within the Aristotelian framework, the moment of a body (*violentia*) was still related to its weight, which, in this case, varies according to its position' [12]. When speaking of the balance, for example, the idea that force (*violentia*) increases with distance from the point of support (*fulcrum*) follows Aristotelian logic: a weight placed farther from the center of a balance requires a greater force to counterbalance the other side, because the system would exert more '*violentia*' in returning to the center, Figure 10.

In the figure, let B be the center (or the point that divides the arms of a scale); QBA the vertical line (or, to speak more correctly, the axis of the horizon, in Benedetti's own words); BC an arm of the said scale; upon C let there be a weight; CO the line of inclination or path toward the center of the world, with which the arm BC forms a right angle at point C. Benedetti states that 'every weight placed at the extremity of any arm of a scale possesses a gravity [effective weight] that is greater or lesser, according to the different ratio of the position of the arm itself' [21, p. 141]. According to Benedetti, with the arm BC in such a position, weight C will be heavier than in any other position, because it does not rest at all upon the center B, as it would in any other position.

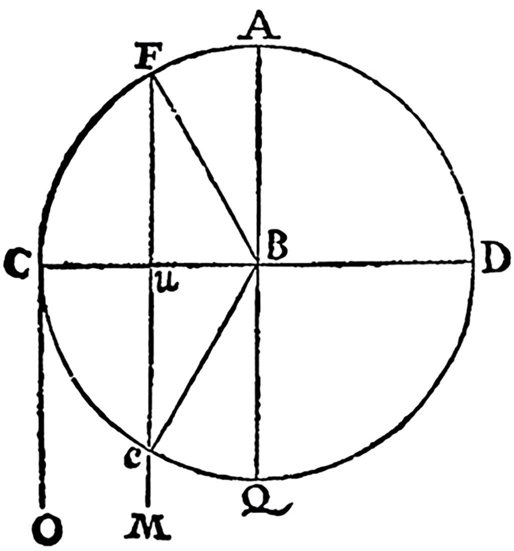

Figure 10: Diagram representing the demonstration given by Benedetti on the weight problem, Benedetti's solution expresses that the body depends on the distance from the fulcrum [12, p. 61].

Benedetti then proposes an example: suppose that the said arm is in position BF, with the same weight at point F, and the line of path or inclination of the referred weight is FuM. Along this line, the said weight cannot progress unless the arm BF were to become shorter. From this, it will be clear that weight F rests somewhat upon the center B by means of the arm BF. According to him, it is quite true that the weight C itself does not advance along the [straight] line CO, because the path of the extremity of the arm is circular, and CO is tangent at a single point. Let this path be ACQ. It is now necessary to presuppose that the weight at the extremity of the arm must rest more upon the center B the closer the line of its inclination (let us suppose FuM) is to the said center [21]. As, for example, let F be over point u, a midpoint and equitable between C and B; therefore, uB will be equal to uC, from which it follows that the said weight will be heavier in the part FC than in the part AF, and [will rest] less upon the center B in the said part FC than in the part AF, where it would be at rest.

And the said arm, the more horizontal it is starting from position BF, the less it will rest upon the said center B and, for this reason, it will also be heavier; and the closer it is to A, starting from the said [point] F, the more it will rest upon the center B, whence it will also be that much lighter. I say the same of every position of the arm throughout the lower rotation CQ, where the weight will hang from center B, pulling the said center in the same way that it pushed it from above. Benedetti then attempts to establish the exact proportion between the weight at the horizontal and the weight as a function of the angle; he seeks to show that the effective force of the weight decreases in the ratio between the total radius BC and the horizontal distance to the center Bu. His property is that 'the proportion of the weight at C to the same weight at F will be as that of the total arm BC to the part Bu, situated between the center and the line FuM of inclination, which the weight would freely travel from the extremity F toward the center of the world'. To prove his claim, Benedetti supposes yet another situation according to Figure 10: let us imagine the other arm of the scale BD, and at the extremity D a weight smaller than weight C is placed. Since the part Bu is smaller than BD, it will be clearly recognized, from Archimedes' first book on weights, that if weight C itself were placed at point u, the scale would by no means move from its horizontal position.

But it is the same thing whether weight F (equal to C) is at the extremity F in the position of the arm BF, as if it were at point u in the horizontal position Bu. As evidence of this, let us imagine the perpendicular wire Fu, from whose extremity u hangs the weight that was at F; whence it will be clear that it will produce the same effect as if it were at F. Which, as we have already said, in relation to point u of the arm Bu, is as much less grave [heavy] than in position C, as Bu is smaller than BC. I assert that if the arm were in position eB, which we may easily recognize if we imagine a wire hanging from point u itself of the arm BC and extended to e, perpendicularly, from which a weight equal to weight C were hung, and free from the arm Be, the scale would remain horizontal with BD. But if the arm Be were consolidated [fixed] and, with weight C applied at e, free from the wire, it would neither rise nor fall; because it is the same whether it is hanging by the wire that hangs from u, or whether it is itself hanging freely at the extremity of the arm Be. And this would proceed from the fact that it would hang little from the center B.

And although the arm BC is called horizontal, assuming it forms a right angle with CO, whence it follows that the angle CBQ is less than a right angle – due to the amount of an angle equal to that which the said [lines] CO and BQ constitute at the center of the elementary region [the center of the Earth] – this, however, matters not, since the said angle is of insensible magnitude. From these reasons, however, we can conclude that, if point u is exactly in the middle between center B and the extremity C, the weight at F or at M will hang or rest by half upon the said center B; and if the said u is closer to B than to point C, it will hang from it or rest upon it more than half; and if it is more toward C, it will rest upon it less than half.

What Benedetti is saying here is basically that the 'effective weight' (motive virtue) is directly proportional to the horizontal distance from the center. If we consider the halfway point of the horizontal path (u at the midpoint), the weight loses half of its force to the central support. And the conclusion the physicist reaches is that *the quantity of any weight, or its motive virtue in relation to another quantity, is known by means of the perpendiculars drawn from the center of the scale to the line of inclination* [21]. This final highlighted sentence is the classical definition of what we today call the Torque Arm; Benedetti establishes that, to calculate the force of a lever, it is necessary to measure the perpendicular distance between the fulcrum (center) and the line of action of the force (line of inclination).

Glossary

In the sixteenth century, the distinction between 'cause of motion' and 'state of motion' was still under dispute. The term violentia, for example, at times referred to the impressed force, and at other times to the regime of motion resulting from the action of an external agent that induces a body to move against its nature. The inclusion of this glossary is justified by the polysemy of Latin terms in the transitional period of natural philosophy. Unlike post-Newtonian physics, where force and momentum have strict mathematical definitions, sixteenth-century mechanics employed terms such as violentia and momentum interchangeably in different contexts (in statics or in dynamics), thus requiring a clarification of these terms within the context of the present study in order to avoid interpretative ambiguities.

Pendulum – Before anything else, it is necessary to clarify the meaning of the central object of our discussion: the pendulum. The word 'pendulum' comes from the Latin *pendulum*, which literally means 'that which hangs' or 'that which remains suspended'; this term derives from the verb pendere, meaning to hang or to be suspended. The term began to be used explicitly to designate the oscillating object between the late Middle Ages and the early Modern period, but its scientific and technical use was consolidated in the early 17th century, primarily due to the work of Galileo, although he was not the creator of the term.

Momentum – In the theoretical mechanics of the 16th century, the word momentum (from the Latin movimentum, derived from movere) was deeply connected to statics and the operation of balances. For example, consider an equal-arm balance in perfect equilibrium: when a weight is added to one of the pans, the balance loses equilibrium and begins to oscillate. This element that breaks stability and initiates motion was called momentum. In the theoretical mechanics of that period (influenced by the rediscovery of Greek texts such as those of Archimedes), momentum was not merely the weight itself, but the effectiveness of that weight in producing motion. Thus, momentum was the tendency or the "will" of a body to descend, increased by its distance from the point of support. As Guidobaldo del Monte said,

> *For momentum in mechanics is the same as propensity in natural things; as when a heavy body, not being in its natural place, strives to move toward it. [...] Every motion, therefore, that originates from a momentum [such as the imbalance of a balance], is outside nature and, for that reason, violent* [21, p. 7].

Violentia – Whereas in modern mechanics *force* is the causal agent that produces acceleration, in sixteenth-century mechanics *violentia* describes the regime of motion imposed on a body, sustained by an impetus that draws it away from its natural place.

Virtus Movens – In the context of 16th-century mechanics, the term 'Motive Virtue' (virtus movens) refers to what we would today call Torque or the Moment of a Force. For Benedetti and his contemporaries, it was not merely a 'force', but rather an intrinsic capacity that a weight possesses to generate motion (or equilibrium) in a lever.

Fulcrum – It is the support point or pivot on which a lever rotates or balances.

In its first version, described in 1602, the pulsilogium was a rudimentary device consisting simply of a cord with a lead weight attached to its end, suspended alongside a horizontal ruler or graduated rod. To use it, the physician placed one hand on the patient's pulse to feel the beats and, with the other hand, manually adjusted the length of the cord along the ruler. Although revolutionary, this initial model was cumbersome, difficult to handle at the bedside in hospitals, and prone to reading errors if the cord was not perfectly stretched, among other problems.

Recognizing the practical limitations of the horizontal ruler, Sanctorius improved the instrument by creating a version with a circular dial, resembling the design of a clock face (see Figure 11). In this improved model, the upper end of the pendulum cord was connected to a small internal spool or rotating shaft. On the front of the mechanism, a circular graduated scale and a pointer attached to the shaft were installed. Instead of pulling the cord manually, the physician now turned a small knob or crank. This motion wound or unwound the cord around the spool, changing the length of the pendulum swinging below and simultaneously moving the pointer across the dial.

When the oscillation of the weight synchronized with the patient's pulse, the physician stopped turning the knob and simply read the value indicated by the pointer on the circular scale. This modification transformed the pulsilogium into a compact, portable, and easy-to-read instrument, which contributed to its widespread use in hospitals for performing more precise clinical examinations.

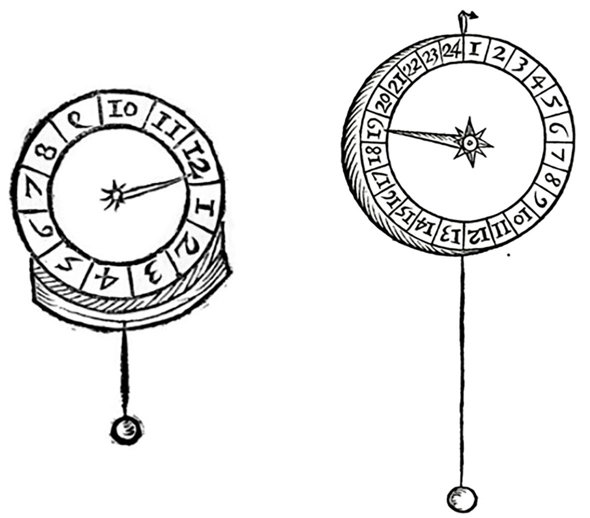

Figure 11: Variants of Sanctorius's pulsilogium. In this engraving, we find two types of pulsilogia with dials; the instrument on the left has a dial divided into 12 degrees, while the one on the right has a dial divided into 24 degrees [12, p. 71].

Data Availability

The entire dataset that supports the results of this study was published in the article itself.

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