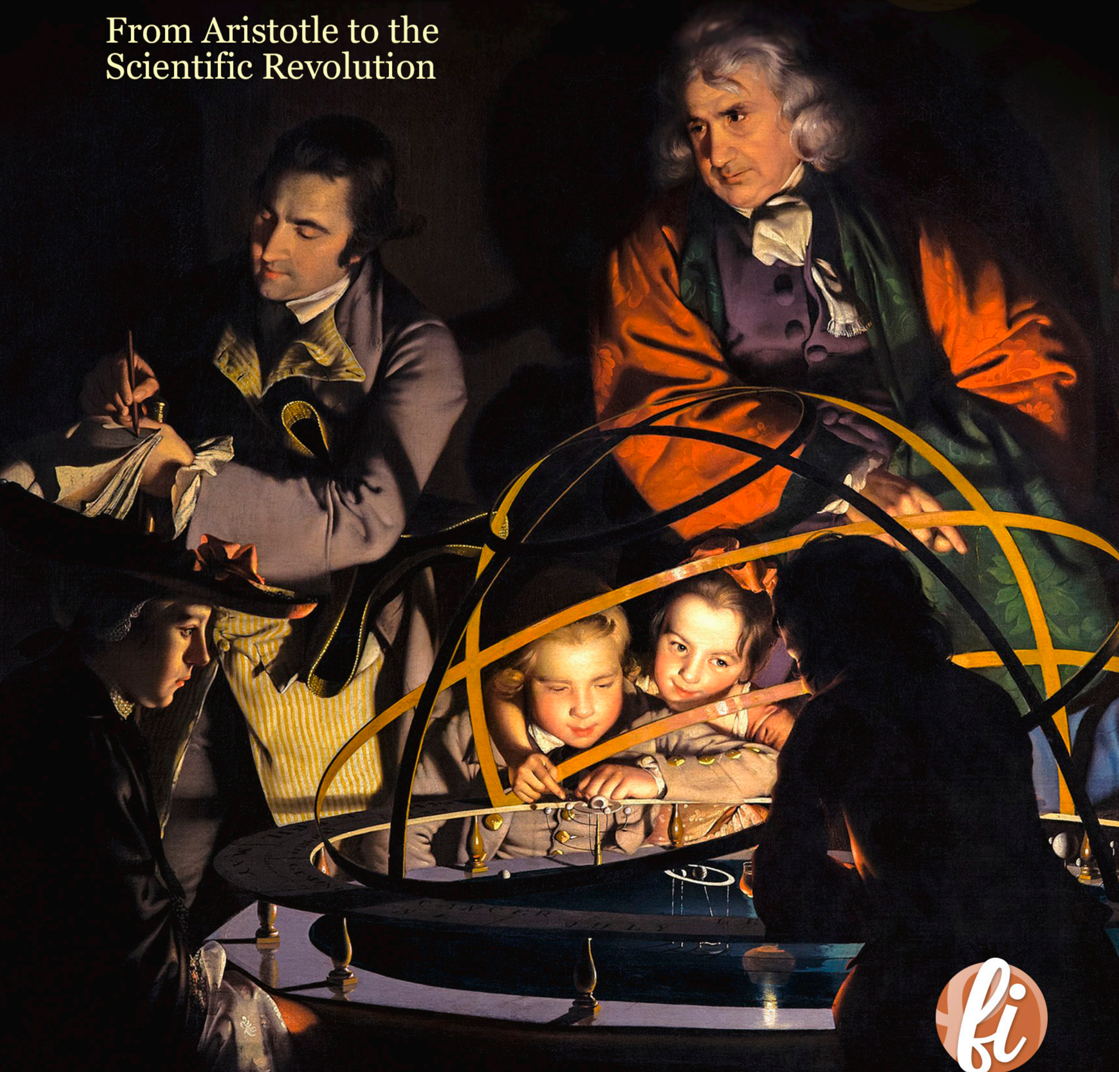
CLASH OF SCIENCES

From Aristotle to the Scientific Revolution

Guilherme Nunes Pires



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FROM ARISTOTLE TO THE SCIENTIFIC REVOLUTION

Guilherme Nunes Pires

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“This was the greatest progressive revolution humanity had known until then; it was a time that demanded giants and forged giants through the power of thought, through passion and character, through universality and scholarship”.

Friedrich Engels

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PREFACE

Guilherme Nunes Pires [1]

This book is an introductory guide to understanding a centuries-old and complex phenomenon: the transition from pre-modern science to the establishment of scientific thought in the early stages of modernity. This process, as we know, is neither linear nor peaceful. It is, above all, a turbulent phenomenon, marked by intense debates and clashes. All of this revolves around a question humanity has pondered since its beginnings: how can we coherently explain the reality around us?

To answer this question, modern thinkers had to direct their efforts against Aristotle. This was because the Greek philosopher offered the most comprehensive and coherent explanation of the world, one that remained dominant for over eighteen centuries. The process of refuting Aristotle's thought took centuries to materialize, beginning with the fundamental challenges posed by Islamic thinkers during the so-called Islamic Golden Age, between the 8th and 13th centuries.

Islamic thinkers played a crucial role in enabling European Renaissance thinkers to begin the definitive challenge to the Aristotelian worldview, paving the way for the modern Scientific Revolution.

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It was within this context of *everyone against Aristotle*, combined with the fundamental elements of capitalism in its mercantile stage, that the Scientific Revolution flourished, laying the foundational pillars of modern science in its classical period (*classical science*).

The aim is to expand the understanding of this phenomenon by emphasizing the ontological and epistemological elements in the formation of modern (*classical*) science. These elements would later be heavily criticized and (almost) surpassed with the advent of *complexity science* (subject of another book).

INTRODUCTION

Since its inception, modern science has played an increasingly prominent role in uncovering the once-mysterious mechanisms that operate in nature and society during the modern period of human civilization. Grounded in principles like *certainty*, *stability*, and *predictability*, early-stage modern science was able to offer tremendous advancements in understanding and controlling nature—achievements that other forms of knowledge, such as magical and religious thinking, could never provide.

Born from a long process of maturation and formation, beginning with the so-called Scientific Revolution, which took place between the 16th and 18th centuries in Western Europe, thinkers such as Galileo Galilei (1564-1642), René Descartes (1596-1650), and Isaac Newton (1643-1727) laid the foundations for establishing the general principles that became the cornerstone of scientific thought in the modern era. These principles stood in contrast to those of pre-modern science formulated in ancient Greece (Koyré, 1957; Henry, 2002).

Pre-modern science, predominantly established through the thought of Aristotle (384 BCE – 322 BCE), was grounded in the understanding of an ontological duality[1] between the earthly and

[1] Ontology "refers to general considerations about existence and reality. In the case of the ontology of social being, the term ontology refers to the determinations that distinguish society as a form of being, naturally marking its difference in relation to antecedent forms of being" (Medeiros, 2016, p. 171). In the case at hand, it refers to the considerations regarding the distinction between the existence of the earthly world, where humans live, and the celestial world, where the stars, planets, and the sun reside.

celestial worlds, each endowed with different matter and laws of motion. Furthermore, Aristotelian science was qualitative rather than mathematical, perceiving reality as imbued with value, harmony, and perfection. Cause-and-effect relationships were seen as having a teleological nature. Physical phenomena were explained based on the most immediate human experience: a clear example of this is the perception of the Earth's immobility, which supported the geocentric cosmology. With such attributes, this pre-modern science remained the dominant form of knowledge for explaining reality for over eighteen centuries, until the advent of the modern period[2] (Reale, 1985; Porto, 2009).

It is against this worldview that the leading figures of the Scientific Revolution in the modern period waged their intellectual battle. Some of the changes that occurred included a lack of concern for questions of value and harmony, the need to abstract the qualities of objects under analysis, the understanding that the universe is made of the same matter and governed by the same laws, the systematic use of mathematics, controlled experiments, and the formulation of general laws, among others.

It is from this new approach that the foundations of science were reoriented in the modern period. The principles of this scientific perspective, commonly referred to as mechanical or classical science (in reference to classical physics), are primarily based on atomism, reductionism, and determinism.

---

[2] It is important to note beforehand that other perspectives for explaining reality existed, particularly Neoplatonic formulations. However, the historiographical literature on science argues that Aristotle's thought was the most comprehensive theoretical and philosophical elaboration and was hegemonically established to explain the phenomena of reality until the beginning of the modern period.

This new scientific stance views reality as composed of indivisible entities that combine to form the structures observed in reality. These entities possess their own properties, independent from one another, and do not produce qualitatively new properties through their relationships, thus grounding this perspective in atomism.

Scientific understanding, then, is achieved by analyzing the constituent parts of something, understanding their mechanisms, and explaining the whole as an aggregate effect of these parts. Macroscopic phenomena are explained by the aggregate of microscopic phenomena, which aligns with the principle of reductionism.

Cause-and-effect relationships are seen as mechanical, linear, and unbreakable, and scientific laws are deduced from empirical regularities. These laws are understood as deterministic and absolute: knowing the initial conditions of a system allows one to predict its future developments with high accuracy.

In this view, both natural and social reality, no matter how complex, is understood as a collection of parts that can be scientifically and analytically understood in isolation and reconstituted through aggregation, leading to the deduction of universal and deterministic laws. In the physical realm, this means analyzing the individual trajectories of bodies in motion; in the social realm, it means analyzing the behavior of individual people (Prigogine; Stengers, 1984, Ulanowicz, 2009; Prado, 2011).

This approach made it possible to generalize global conclusions from local experiments in the natural sciences and to understand

societal dynamics as an effect of the aggregated behavior of individuals. This scientific worldview has dominated for centuries and still holds a certain degree of hegemony in various fields of knowledge in the 21st century.

The aim of book article is to trace the transition from pre-modern science to the establishment of modern scientific thought. While many scholars have focused on the general elements of modern science's formation as a body of rational knowledge—such as the use of mathematics and the critique of Aristotelian thought—the ontological discussion is often overlooked (Koyré, 1957; Henry, 2002).

Our contribution lies in understanding the ontological foundations of modern science's formation and its monumental clash with Aristotelian thought, i.e., the revival of atomist ontology, the principle of reductionism for analyzing reality, and the modern conception of causality and scientific laws. More than that, it is also argued that scientific inquiry are closely related to the established social relations.

This book is divided into three chapters, in addition to the introduction and conclusion. The first chapter presents the general elements of Aristotle's intellectual dominance as a scientific explanation of reality. The second chapter explores the transitional elements leading to modern scientific thought, including the contributions of Islamic thinkers and the European Renaissance. Finally, the third chapter outlines the ontological foundations of the Scientific Revolution and the birth of modern science.

1

PRE-MODERN SCIENCE: ARISTOTELIAN HEGEMONY

Understanding the establishment of scientific foundations in modernity requires a necessary reconstruction of the key antecedents that enabled the evolution of scientific thought, ultimately leading to modern science. Thus, some considerations about pre-modern scientific discourse must be made.

This discourse finds its greatest expression in the thought of Aristotle (384 BCE – 322 BCE), in his attempt to understand and explain the cosmos as a rationally ordered and harmonious whole. Aristotelian thought, which provided a comprehensive explanation of physical phenomena and the organization of the Universe, remained hegemonic from the 4th century BCE until the 16th century CE. Despite successive changes in economic, social, religious, and cultural structures, Aristotle's thought was only surpassed with the rise of capitalist society and the Scientific Revolution of the 16th century, along with the profound transformations they brought about (Porto, 2008).

Figure 1 – Aristotle (384 BC – 322 BC).

However, the positivist conception of the historiography of science tends to view the development of scientific thought as a kind of linear evolutionism, in which pre-modern scientific ideas are often seen as primitive conceptions of human understanding. Contrary to this view, the richness of the Aristotelian worldview

reveals a well-articulated and rigorous theoretical construction for explaining reality. More than that, this thought was established as:

> (...) a complex theoretical construction, deeply integrated with an extremely comprehensive philosophical framework, and developed from the empirical elements provided by the most immediate human experience. The intellectual strength of this thought, rooted primarily in its breadth and strongly organic nature, ensured its primacy as a systematic form of scientific knowledge for approximately eighteen centuries (Porto, 2009, p. 1).

Or, according to the French historian of science Koyré (1943a, p. 337-338):

> I would like to stress, because it is fairly widely mis appreciated, that the Aristotelian physics is a very thoroughly thought out, and very coherent, body of theoretical knowledge, which, besides having a very deep philosophical foundation, is (...) in pretty good accordance (...) with the experience, at least with the commonsense experience, of our everyday life.

At another moment, Koyré (1943b, p. 407) argues that Aristotelian science:

> is false, of course; and utterly obsolete. Nevertheless, it is a “physics”, that is, a highly though non-mathematically elaborated science. It is not a childish fantasy, nor a brute and verbal restatement of common sense, but a theory, that is, a doctrine which, starting of course with the data of common sense, subjects them to an extremely coherent and systematic treatment.

Aristotle's science, unlike the notion of science that emerged during the Scientific Revolution of the sixteenth century, is characterized by its qualitative and non-mathematical nature. While modern scientific discourse is based on quantitative formulations,

Aristotle sought to uncover the essence of phenomena. We think of physics, for example, as "the science of nature understood in the sense of Galileo, that is, considered quantitatively. In contrast, Aristotle's position is diametrically opposed; his physics is not a quantitative science of nature, but a qualitative one" (Reale, 1985, p. 70).

According to Prado (2011), the impossibility of mathematizing Aristotelian science arises from the inability to abstract the determinations of reality. This occurs because “[t]he characteristic mathematization of modern science presupposes that the qualities of objects inhabiting the world of experience can be abstracted and thus subsumed under quantitative determinations through operations of reduction (...)” (Prado, 2011, p. 99).

In contrast, the science of the Greek thinker is grounded in a holistic conception of an ordered, finite, and hierarchized cosmos. More than that, the Aristotelian cosmos “has ethical and aesthetic value, carries meaning and purpose, and is associated with the idea of harmony and perfection” (Prado, 2011, p. 99).

Compared to modern scientific rigor, Aristotle's work is more than a quantitative explanation of nature; it is, above all, an ontology of the suprasensible and sensible reality. This is why Aristotle’s Metaphysics and Physics (2002; 2009) maintain a close relationship. Although Metaphysics (first philosophy) deals with suprasensible or metaempirical questions, and Physics (second philosophy) addresses sensible or empirical questions, both texts and themes are deeply interconnected in Aristotle’s thought (Reale, 1985).

In Aristotle's science, movement, understood as change in general, affects all existing matter in the terrestrial world. How then can we coherently explain processes of change and transformation? Or better yet, in the words of Porto (2009, p. 2), “how can something that is cease to be?”

While the school based on Heraclitus's thought (circa 500 BCE-450 BCE) defended the notion of perpetual movement of reality, and the Eleatic School denied movement (a static reality), Aristotle develops the idea of potential being and actual being to address this problem (Porto, 2009).

Movement “is observable locally and temporally in nature, but it always has its own meaning within the cosmic order” (Prado, 2011, p. 100). It can be said that an apple seed, for example, will not randomly become another fruit tree; rather, it will become exactly what it has the potential or purpose to be, that is, an apple tree. In any seed, the plant is not yet developed but possesses the capacity to become so. Aristotle argues that there is a mode of potential being here. The development (change) from the seed to the plant characterizes the mode of actual being. “[T]here is an element of causality in the seed, defined by its essence, which will determine its evolution” (Porto, 2009, p. 2). Therefore, causality has a teleological character.

In discussing change, characterized by the movement from potential being to actual being, Aristotle identifies four types in which these changes can occur: “birth (generation) and destruction (corruption), changes of qualities (alteration), changes of size

(growth or diminution), and displacements (which Aristotle termed local movements)" (Porto, 2009, p. 3).

In contrast to modern science, movement is a process of change that opposes the state of rest. Movement is change. Not only is it a change of position in a neutral geometrized space, but also a change within itself. A moving body undergoes change not only spatially in relation to other bodies but, above all, "undergoes itself a processus of change" (Koyré, 1943a, p. 338).

Moreover, movement "always affects the body which endures it, and, consequently, if a body is endowed with two (or more) movements, these movements interfere with each other, impede each other, and even are, sometimes, incompatible with each other" (KOYRÉ, 1943a, p. 338).

According to Reale (1985), these considerations lead to the problem of the four causes proposed by Aristotle. For the Greek thinker, there is no movement or change without a cause. However, a single driving cause for the occurrence of movement is not sufficient for peripatetic thought. The becoming of things necessarily respects a finite quantity of causes. These are: (a) material cause; (b) formal cause; (c) efficient cause; and (d) final cause.

The first and second relate to the matter and form (essence) that constitute all existing things. The third pertains to the external force with which the object must follow its development. The last refers to the purpose that everything serves, implying a teleological causality. In summary, the material and formal causes relate to the *being* of things, while the efficient and final causes relate to the *becoming* of things (Bunge, 2009).

It is important to emphasize that Aristotle’s conception of cause cannot be equated with the conception that emerges with modern science. From the modern scientific perspective, cause is synonymous with an external agent causing the result. This view of causality is only one—the efficient cause—among the others in Aristotle’s framework. For the Greek thinker, cause can also mean “principle that determines or structures the thing” (Porto, 2009, p. 3).

Given these considerations, Bunge’s synthesis (2009, p. 32) is suitable for understanding the four causes:

> [T]he material cause (the scholastic *causa materialis),* which provided the passive receptacle on which the remaining causes act- and which is anything except the matter of modern science; the formal cause *(causa formalis),* which contributed the essence, idea, or quality of the thing concerned; the motive force or efficient cause *(causa efficiens),* that is, the external compulsion that bodies had to obey; and the final cause *(causa finalis)* was the goal to which everything strove and which everything served.

According to Porto (2009), these considerations allow for the visualization of the fundamental traits of Aristotle's cosmological conception. This cosmological view is closely linked with Metaphysics and Physics and differs considerably from what will emerge with modern science. First and foremost, it is essential to emphasize that Aristotle's physics and cosmology are a synthesis of the most immediate empirical evidence that human experience can encounter.

This is why, first and foremost, the peripatetic cosmos is filled with matter. The existence of a vacuum was considered absurd from the standpoint of the constitution of the Universe. Nothingness, or

non-being, represents an absurdity in light of the empirical observation that everything that exists is filled with matter. Nature, from this perspective, is imperatively acting to avoid a vacuum (Porto, 2009).

Secondly, Aristotle regarded the idea of an infinite extension of matter as absurd: his Universe is finite. Moreover, “[s]trongly influenced by the paradigm recurrent among the Greeks of perfect forms, Aristotle conceived it as a finite space, fully filled, limited by a sphere to which the stars were connected and centered on the Earth” (Porto, 2009, p. 4).

Time and matter are cyclical and finite substances, respectively: “the Greeks do not know the notion of infinity, either in the temporal realm (time is cyclical) or in the spatial realm (the universe has limits)” (Coutinho, 2018, p. 123).

Aristotle's thought seeks to distinguish between the terrestrial world of humans and the celestial world, marked by the presence of differentiated matter. The Greek thinker attributed the idea of two separate spheres of the world: the sublunar world and the supralunar world. While the former is marked by the terrestrial world, capable of all change and transformation, the latter is immutable and fixed, capable only of circular movements.

The sublunar world is filled with terrestrial matter and the four elements in a continuous state of change: earth, water, fire, and air. In contrast, the supralunar or celestial world is characterized by immutability due to the absence of terrestrial elements, being filled with a differentiated matter known as ether or quintessence (Porto, 2008).

In the sublunar world, one can identify, through the most immediate empirical experience, that all things undergo radical transformations over time. Conversely, for Aristotle, celestial bodies do not undergo transformations, only cyclical physical displacements, without altering their essence. This observation was easy to understand: immediate experience and the temporal existence of human beings indicated that the celestial realm has never undergone essential changes throughout history, while the domain of human beings is in constant movement and change. The terrestrial world, therefore, is made of corruptible matter, continuously subjected to the processes of generation and destruction. The celestial world, on the other hand, is only subject to local circular movements (Porto, 2009).

In the terrestrial world, Aristotle seeks to explain the hierarchical order of the elements through the "theory of natural movements." Aristotle conceived of "the realm of being (the 'natural place') to which a given body belongs by its nature" (Koyré, 1943a, p. 338). The elements of the sublunar world form concentric layers, where heavier elements, such as earth, tend to be in the innermost layers, while lighter elements, such as fire, would be in the outer layers.

Displaced from their natural place, the elements tend to return to their original location: "fire and air tend upward, while earth and water tend downward. Up and down are not relative concepts for us, but objective realities; they are natural determinations" (Reale, 1985, p. 74).

The space through which objects move is characterized by being qualitatively differentiated at each geographic point. In other words, places have their own nature and uniqueness, with which objects move through time and space. According to Porto (2009), these attributes concerning space (place) distinguish Aristotelian science from that which emerges in the modern period. The latter is endowed with the capacity to: (1) abstract the attributes of objects; (2) conceive of space as abstractly homogeneous, represented geometrically.

Given these considerations of movement and space, Aristotle understands that the fall of solid bodies is explained by the necessary tendency of the body to return to its natural location. The heavier the body, the greater its speed of fall. Furthermore, the fall of solid bodies does not pertain to falling towards the center of the Earth, but rather to the center of the Universe. Therefore, Aristotle (2014) asserts the immobility of the Earth and its centrality in the Universe.

The empirical argument for the Earth's immobility is as follows: if the planet were in motion, when an object is thrown upward (to a considerable height), it should fall at a point distant from its launching location. Since empirical experience contradicts this thesis, it is natural to conclude that the Earth is an immobile body. This simple idea, which can be empirically verified through immediate human perception, persisted for centuries in defense of geocentrism and would only be overturned by the Copernican revolution and the idea of inertia (Porto, 2009).

According to Prado (2011, p. 101):

> Within Aristotle's conception of the world, the principle of inertial motion as understood by modern thinkers appears not only impossible but also absurd. Nothing has continuity, not even the simplest movement, spontaneously and automatically. Every movement is a process of change that requires, for its persistence, the continuous action of a cause that acts productively. As soon as the cause, whether internal or external, ceases, so too does the movement.

An example of violent movement was "provided by throwing a solid object upward. Being made of heavy matter (earth), the natural movement of this object would be to fall toward the center of the Universe and, consequently, toward the surface of the Earth" (Porto, 2009, p. 6). Thus, "the upward movement, that is, the movement away from the Earth, was an unnatural movement; its cause could not be found in the essence of the being itself but was external to it" (Porto, 2009, p. 6).

A fundamental point of Aristotle's science is the explanation of movement in the supralunar world. Capable only of local circular movements, celestial bodies were held within crystalline spheres, orbiting and following the observed trajectories of the planets. Introduced by the Greek astronomer Eudoxus (circa 408–355 BCE) to explain the movement of the stars, Aristotle adopts the model of crystalline spheres.

Through the model of crystalline spheres, "Aristotle attributed the movement of the celestial spheres to Intelligences, hierarchically inferior to a First and Supreme Intelligence" (Porto, 2008, p. 3). However, according to Reale (1985), Aristotle later corrects his cosmological model based on new discoveries by Greek astronomers, establishing "the number of spheres at fifty" (Reale,

1985, p. 65). Subsequently, with further discoveries, he states that “fifty-five supersensible substances move the corresponding 55 spheres” (Reale, 1985, p. 65).

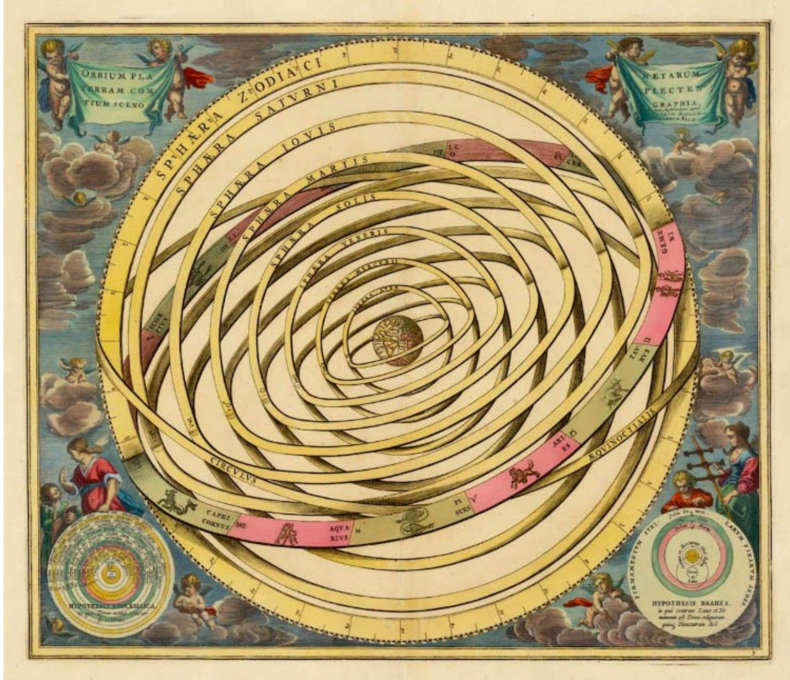

Figure 2 – Aristotelian Ptolomaic Cosmos.
Source: Harmonia Macrocosmica (Cellarius, 1660).

The tension between the Aristotelian cosmological model and the increasing complexity of the celestial world, due to new astronomical evidence, was resolved through the synthesis proposed by the Greek astronomer Claudius Ptolemy (90 AD – 168 AD) in the 2nd century AD. The Ptolemaic geocentric model defined that “for each planet, the composition of a revolution (epicycle) around a certain point, which, in turn, described a circular trajectory (deferent) around another center” (Porto, 2008, p. 3). Furthermore,

the model proposed that although celestial bodies were centered on the Earth, the planet did not remain at the center but was instead positioned at a slightly displaced point called the *equant*.

Aristotle's scientific explanation of phenomena and the geocentric model was hegemonically dominant for centuries. The Aristotelian worldview and its science served as the primary explanatory framework for the order of the cosmos until the early modern period. Gradually, the hegemonic Aristotelian thought was questioned and challenged at various points during the period from the late Middle Ages in the Islamic Renaissance to the European Renaissance in the 14th century, culminating in its effective refutation in the 16th century.

2

THE RENAISSANCE(S) AND THE TRANSITION TO MODERNITY

Aristotle's science and the geocentric model became the hegemonic worldview for explaining the cosmos. The theoretical and philosophical coherence, along with its status as "proven" by immediate empirical experience, allowed this explanation of the universe to prevail even through the decline of Classical Antiquity (8th century BC - 6th century AD) and the rise of the Middle Ages (6th century AD – 14th century AD).

As Coutinho (2018, p. 115) notes, during the early medieval period—known as the High Middle Ages, from the 6th to the 10th centuries—the development of original scientific and philosophical ideas was practically nonexistent. Libraries were very limited in resources; one of the largest from that time contained “only three hundred volumes—mostly related to logic, rhetoric, and grammar, which were part of religious education” (Coutinho, 2018, p. 115).

The most significant discussions were theological, focusing on “predestination” and “free will,” particularly influenced by the work of Saint Augustine (354 – 430). On one hand, the decline of the urban civilization of Classical Antiquity gave way to a civilization based on feudalism and monasteries, predominantly rural in character. This decline in productive forces considerably impoverished social relations during this period. On the other hand, the Catholic Church began to exert maximum ideological control through its monopoly on education; consequently, “the overwhelming majority of the

population, including the nobility and even kings (like Charlemagne), were illiterate. Only members of the clergy (and even then, not all) were literate" (Coutinho, 2018, p. 115).

However, certain changes began to be made to the worldview to align with the new economic, political, religious, and cultural structure that characterized the medieval era. Aristotle's scientific explanations, while heavily influenced by Plato (428/427 BC - 348/347 BC) during the medieval period, remained the most coherent theoretical framework, although the main focus shifted to the divine realm.

Whereas in antiquity, the cosmos was endowed with objective rationality—a universal expression found both in the world and in humans—during the medieval period, this rationality was transformed into a divine endowment. Thus, the perception of the cosmos as a rational, ordered, harmonious, and perfect whole was abandoned, and it came to be understood as "a product of divine creation, such that it could only be properly understood through the lens of Scripture" (Prado, 2011, p. 89).

According to Prado (2011, p. 88), in the medieval period, "man felt at home in a world whose final cause was God, such that philosophical reflection primarily took the form of a religious cosmology." In this context, "[the] Earth was considered the spatial center of the cosmos, and humanity itself was viewed as its significant center, as everything was related to its existence and destiny within the divine order" (Prado, 2011, p. 88).

Reflection still grappled with cosmic questions through the Greek legacy, addressing "substance, matter and form, essence and

accident, potency and act, etc., under the assumption that the surrounding universe was comprehensible to the human mind" (Prado, 2011, p. 88), but only through religion and faith, facilitated by the synthesis between Greek thought and Judeo-Christian theology.

2.1 The Islamic Golden Age

However, during the late Middle Ages—between the 10th and 14th centuries—significant "economic and social changes began to reflect in philosophical" (Coutinho, 2018, p. 115) and scientific thought as well. This period marks a resurgence and deepening of the study of Aristotle's ideas, along with their contestation, driven by the pioneering efforts of Islamic thinkers. It is therefore necessary to outline the general features of the challenge to Aristotelian thought posed by Islamic thinkers. This challenge, however, was primarily directed at astronomical formulations.

As Saliba (2007) states, the science of the Islamic Renaissance period between the 8th and 13th centuries was a key source for the scientific development of the European Renaissance from the 14th to the early 16th centuries.

According to Coutinho:

> [t]he first responsible for this 'return to Aristotle,' as well as to Greek culture in general, are Arab thinkers who lived both in the East and, especially, in the part of Spain controlled by the Moors. This is primarily due to the fact that the Arab expansion, which began in the 7th century, led to the Islamic domination of North Africa, where the city of Alexandria was located, home to a vast library largely composed of texts by Greek thinkers (Coutinho, 2018, p. 116).

The Islamic Golden Age was a highly fruitful period for knowledge. During the time marked by the expansion of the Islamic Empire into North Africa and Southern Europe, there was a unique combination of commercial and urban flourishing, alongside an increase in freedom of thought and a celebration of knowledge. The Islamic caliphates showcased their strength in pre-modern scientific development by encouraging free thought (Bennison, 2009).

As Saliba (2007) argues, the Western historiography that addresses Islamic civilization, which he refers to as the "classical narrative," is mistaken in attributing characteristics of a rural, desert, and backward civilization. In this view, such a civilization was only able to develop a scientific tradition through the translation of Greek works. On the contrary, it was precisely because Islamic civilization had already cultivated a conducive environment for scientific knowledge to emerge that the quest for translating Greek writings took place.

Starting in the 8th century, with the capital moved to Baghdad, the Abbasid Caliphate became much more open to the freedom of thought. As a result, there was a massive effort to translate the great Greek works into Arabic, known as the *Translation Movement*[1], the Muslims translated the major works of Greek thought that were available to them, including those of Plato, Aristotle, and Ptolemy (Gutas, 1998).

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1 For a deeper historical understanding of the multidimensional aspects of the movement, see Saliba (2007), Gutas (1998), Algeriani and Mohadi (2017), Khalidi and Dajani (2015), and Sabra (1987).

Figure 3 – Islamic Golden Age.

Thus, the critical incorporation of the Greek worldview was made possible. In the words of Saliba (2007, p. 2), there was an active "appropriation of the sciences of those ancient civilizations through the willful process of translation. And this translation movement is said to have encompassed nearly all the scientific and philosophical texts that those ancient civilizations had ever produced".

As an example, while the synthesis of the geocentric cosmological system found in Ptolemy's *Almagest* and *Planetary Hypotheses* was translated into Western Europe only in the 12th century, these works had already been critically disseminated in the Islamic world since the 9th century (Saliba, 2007). Saliba (2007, p. 75) argues that:

> between 820 and 870, almost all translations shifted, for all practical purposes, from the Persian and Sanskrit as source languages to Greek as the preferred language to be tapped on all levels. (...) The

> success of the latter translation attempt was unparalleled. It included almost all serious philosophical and scientific Greek texts.

Something that was harshly criticized by Islamic thinkers was the contradiction between Aristotelian cosmology and its applicability in mapping the movements of the planets. The astronomer Ibn al-Shatir (1304-1375), for instance, confronted the Aristotelian system at its foundations and even developed a system similar to the Copernican one (ROBERTS, 1957).

According to Aristotle's metaphysics, as outlined in the previous section, the celestial world is composed of a single matter incapable of undergoing generation and corruption, known as ether. Considering this premise, it is impossible for the sun to emit more light than the crystalline sphere that carries it, as both are made of the same celestial matter. Conversely, how could a sphere "that carried the sun (...) emit such a bright light as the light of the sun, from only one part of it, where the sun is located, while the rest of its body acted like a crystalline transparent spherical substance that did not emit any light?" (Saliba, 2007, p. 122).

The Persian thinker Muhammad ibn Muhammad ibn al-Hasan al-Tūsī (1201-1274) developed an alternative cosmological model as a way to surpass Aristotle and Ptolemy. al-Tūsī presented an alternative model for orbits based on a double circle, known as the *Tusi couple*, to more consistently explain the motion of celestial bodies (Saliba, 2007).

The Arab thinker Ḥasan Ibn al-Haitham (965–1040, known as Alhazen in Latin) identified contradictions in the cosmological

model regarding the system of celestial spheres and the empirical reality of the movement of the stars (Saliba, 2007).

The contradictions between the cosmological principles and the physics that characterized the Aristotelian-Ptolemaic model led al-Haitham to understand that a new foundation for science was necessary, “based on the new principles of consistency between the physical reality of the universe we live in and the mathematics one uses to represent that reality” (Saliba, 2007, p. 101). In this new constitution of science, especially in astronomy, “those two fields of science had to be constantly consistent; otherwise, we would end up talking about imaginary motions as was done by Ptolemy” (Saliba, 2007, p. 101).

Other Islamic thinkers also questioned the compatibility between Aristotelian cosmology and Ptolemaic astronomical constructs. Ibn Bājja (Avempace, 1085–1138), Ibn Tufail (1105–1185), Ibn Rushd (Averroes, 1126–1198), and al-Bitruji (?–1204) each highlighted the contradictions within the Greek system in their explanations of the universe (Saliba, 2007). In summary, this period was crucial for paving the way for systematic criticism of Aristotelian science and for laying the foundations for the transition to the modern scientific era in Western Europe.

Although it began in the Islamic Renaissance, the critique of the pre-modern scientific discourse based on Aristotelian science was fundamentally challenged during the European Renaissance. While Islamic thinkers primarily contested this discourse in the field of astronomy—anticipating mathematical quantification and empirical experimentation as vital for a new way of doing science—

the progressive European challenge would take shape not only in astronomy but also in the foundational principles of ancient cosmology.

2.2 The European Renaissance

The European Renaissance is characterized by a resurgence of urban, commercial, and cultural life in the Mediterranean basin. It was a multidimensional and multi-century phenomenon. The Renaissance represented a revival of the enlightenment that began in classical antiquity. The flourishing of cities, urban development, commercial rebirth, and the development of instruments that facilitated communication (such as movable type printing) were some of the prerequisites for creating an environment conducive to free inquiry and the dissemination of knowledge.

During the late Middle Ages, profound social and economic transformations occurred, especially in Western Europe. The feudal economic nucleus experienced a gradual decline with the expansion of commercial activities; the nation-states of the transition from feudalism to capitalism began to emerge; cities flourished; and a new class, the bourgeoisie, arose, bringing with it the seeds of the destruction of the old world.

In the words of Coutinho (2018, p. 123):

> It is in these cities, especially the Italian ones, that the Renaissance begins and finds its greatest flourishing. All of them have a significant and even dominant presence of mercantile and banking capital. In these cities, commerce is the main economic activity, which puts them in contact with different cultures; moreover, or perhaps for this very reason, they are also societies with great internal social mobility,

> where wealthy bourgeoisie count as much or even more than the old rural nobility, and where the most active members of the lower classes can aspire to a rise in the social hierarchy. In short, the Renaissance expresses the emergence of a new social class, the bourgeoisie, to which one belongs not by birth but as a result of social mobility and merit. (It is evident that this mobility decreases, or even extinguishes, as capitalism consolidates.)

This "renaissance" refers to the shared characteristics with classical Greek antiquity, but the fundamental factor is that the emerging new society, unlike the Greek world, is strengthened by commercial expansion. While in the Greek world, commercial expansion was synonymous with decline—because outside the limits of the Greek city-state lay the "barbarians" and the "uncivilized"—for the nascent capitalist society, it was a factor of strength and progress. This is one reason why Greek cosmology favored a closed, spherical, and cyclical universe: "The narrow limits of the Hellenic city-state lead to the idea of a closed world" (Coutinho, 2018, p. 123).

In the period of the European Renaissance, on the other hand, mercantile expansion became a fundamental factor for the formation of the emerging capitalist society. It is during this time that overseas expansion will begin in search of establishing a global market. Unlike the social formation of the Greek world, capitalism "points towards the commercialization of the entire world, towards the creation of a global market" (Coutinho, 2018, p. 124). It is in this context that one can assert the existence of an infinite universe without a center, contesting geocentric cosmology.

As will be seen, one principle of extreme novelty and importance in the transition to modernity is the idea of an infinite universe.

Another unprecedented and fundamental principle is the conception of individual autonomy. That is, the human being is viewed as an autonomous and free entity in an infinite universe. The rigid hierarchy of feudal status is broken, giving way to the condition of the individual who is capable of social ascension (albeit only in principle). The emphasis on the autonomous and free individual, as we will see later, has strong roots in the formation of modern atomist ontology in physics.

Unlike feudalism, there is no eternal social condition based on birth: “someone who is born poor can become rich, a craftsman can become a businessman, or an impoverished noble can turn to trade” (Coutinho, 2018, p. 124). The notion that “man is free, that he can put in his effort and merits to rise socially and develop his personality in an infinitely open world, is the theoretical expression of the real possibilities contained in the nascent bourgeois mercantile economy” (Coutinho, 2018, p. 124).

It is in this context that the fight against geocentrism also becomes a hegemonic struggle between worldviews. A battle waged between the Aristotelian cosmology of a finite universe, centered on Earth and enveloped by spheres, and the new vision of an infinite world inhabited by autonomous and free individuals (Coutinho, 2018).

In other words, it is a battle between the feudal, aristocratic, and religious worldview and the new bourgeois perspective: “a struggle for the truth of experience and reason against the authority of the Bible and the Church” (Coutinho, 2018, p. 125). Moreover, it is a clash between the “new bourgeois vision of the world (which affirmed the existence of a free man at the center of an infinite

universe) and the old aristocratic-feudal conception (which assigned man a fixed and predetermined place in a hierarchized and closed universe)” (Coutinho, 2018, p. 125).

With these characteristics, the European Renaissance marks a new historical stage of social development, transforming all aspects of social activity. For instance, the commercial and cultural flourishing at its onset paved the way for the poetic and narrative blossoming of figures such as Francesco Petrarca (1304-1374) and Giovanni Boccaccio (1313-1375). From the perspective of painting, there is a radical transformation in how space is conceived, now open and infinite, reflecting the autonomous and free human being.

> One only needs to compare, for example, Giotto (1266-1337) with Piero Della Francesca (1416-1492). Giotto paints a fixed world where the outer space is used merely as a decorative backdrop. His characters are generally placed hierarchically, clearly indicating their position in the social hierarchy; they are more like species, or members of a social estate, than individualized persons. In contrast, with Piero Della Francesca — and even more so in the works of Flemish painters or later Italian artists (like Leonardo, Botticelli, etc.) — we see the emergence of men and women who are quite individualized (the extreme realism of the Flemish artists, for example, serves to accentuate these singular traits), situated in the center of a depicted space that is rendered in perspective, open, and infinite. To summarize, we could say that the essence of Renaissance thought and art is this: the autonomous and free man as the center of an infinite universe, open to infinite possibilities (Coutinho, 2018, p. 119).

Moreover, the humanist tradition that developed among Renaissance thinkers enabled a fundamental shift in the human position concerning reality. In Antiquity and the medieval period,

the human stance toward the cosmos was one of *vita contemplativa* (contemplative life), which implied a passive role. In the European Renaissance, this position radically shifted to *vita activa* (active life), marking an active stance aimed at transforming reality (Koyré, 1957; Henry, 2002).

During this period, reactions to Aristotelian science became apparent. The French philosopher Jean Buridan (1295–1358) revisited and developed an alternative theory to explain the movements of bodies. He formulated the theory of *impetus* that established that when an object is thrown, the force exerted by the thrower imparts a tendency of motion to the object[2].

Over the course of the movement, this tendency would gradually lose its strength until the motion, deemed unnatural, eventually ceased. "With this approach, the requirement that any unnatural movement necessitates the continuous action of an external force on the moving object was abandoned" (Porto, 2009, p. 6).

Nicholas of Oresme (1323–1382), on the other hand, questioned the Greek cosmological principles based on the immobility of the Earth. In his work *Treatise on the Heavens and the World*, Oresme argued that "it could not be proven by any experience that the Heavens move with a daily motion while the Earth does not" (Porto, 2008, p. 3).

The German cardinal Nicholas of Cusa (1401–1464) was one of the great Renaissance thinkers who significantly challenged the

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2 Over the course of the movement, this tendency would gradually lose its strength until the motion, deemed unnatural, eventually ceased. "With this approach, the requirement that any unnatural movement necessitates the continuous action of an external force on the moving object was abandoned" (Porto, 2009, p. 6).

Aristotelian worldview during the transition to modernity. Contrary to Aristotle's assertions, Cusa proposed that it is impossible to claim that the Universe has a fixed and immobile center. According to Aristotle, the Earth was stationary and held a privileged position at the center of the Universe. In contrast, Cusa posited that, regarding celestial orbits, the Universe is in constant motion and lacks any fixed center.

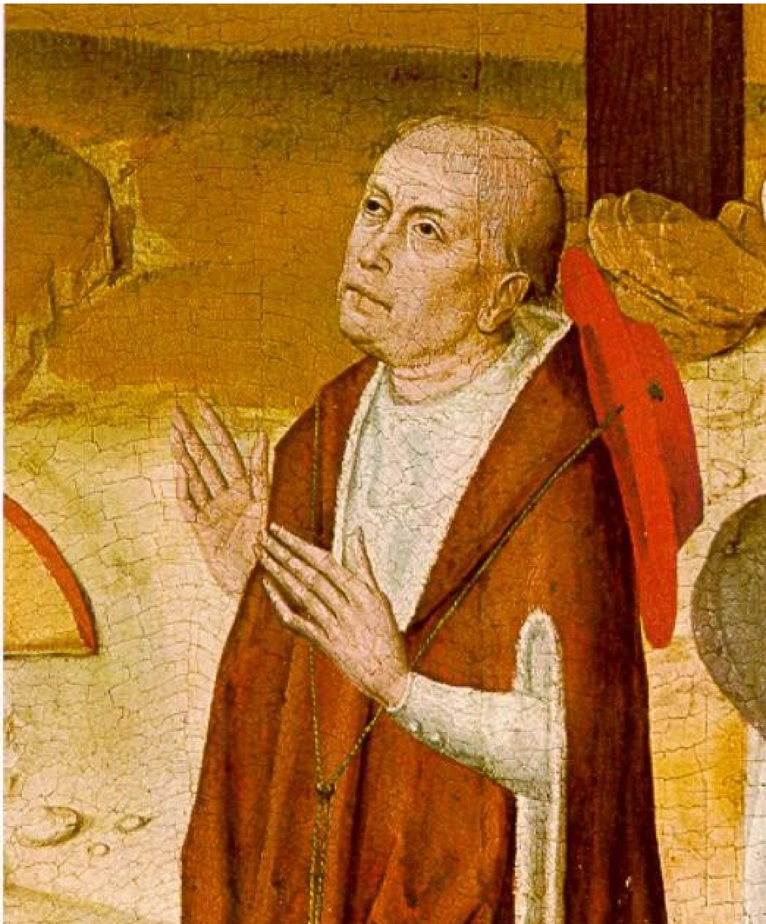

Figure 4 - Nicholas of Cusa (1401–1464).

In Cusa's view, God is the unity of multiplicity and infinite being. Therefore, the real world, the Universe, is also infinite. As Coutinho (2018, p. 127) argues, “by affirming this, he entered into open contradiction with the Aristotelian-Thomistic cosmology. If the universe is infinite, the Earth is not at the center of the world”.

The position of rest and motion, according to his formulations, depends on the observer in question. “Both an observer on Earth and another situated on the Sun would be correct in asserting that they are at the center of the Universe and that everything else revolves around them” (Porto, 2008, p. 3). These attributes are supported by a radical novelty in the history of thought: the idea of infinity.

For Koyré, however, the formulations of Nicholas of Cusa were still far from those found in modern science. While he took a significant step in questioning the Greek worldview by rejecting hierarchically established structures in the Universe, he still believed in the movement of celestial spheres and denied the possibility of mathematical quantification, a characteristic of modern science. Thus, “[h]is world is no longer the medieval cosmos. But it is not yet, by any means, the infinite universe of the moderns” (Koyré, 1957, p. 23-24).

It was the Italian friar Giordano Bruno (1548–1600) who developed the idea of an infinite Universe. A fervent advocate of the new heliocentric astronomy, Bruno made a fundamental break with Aristotelian cosmology by proclaiming a Universe that is infinite, undifferentiated, completely filled, without centers, limits, and devoid of privileged positions in space. In other words, “in Giordano Bruno's Universe, we had a moving Earth traversing a neutral,

centerless, immensely populated, and infinite space" (Porto, 2008, p. 4). In doing so, Bruno rejects the Aristotelian notion of "natural order".

Koyré (1943a, p. 341) summarizes as follows:

> By a stroke of genius Bruno saw that it was necessary for the new astronomy to abandon outright the conception of a closed and finite world, and to replace it by that of an open and infinite Universe. This involves the abandonment of the notions of "natural" places and motions as opposed to non-natural, violent ones. In the infinite universe of Bruno, in which the Platonic conception of space as "receptacle" (χώρα) takes the place of the Aristotelian conception of space as envelope, all "places" are perfectly equivalent and therefore perfectly natural for all bodies.

Figure 5 - Giordano Bruno (1548–1600).

Bruno, however, did not make significant contributions to the emerging modern science and was even considered "not a very good philosopher," in Koyré's words (1957, p. 54). The lack of important contributions to the rise of modern science can be attributed to his failure to understand mathematics as a fundamental factor for the new science in his theoretical reflections. "Unlike those who advocated for mathematical knowledge (such as Galileo, Descartes, and Spinoza), he argued that mathematics serves to manipulate objects but cannot explain them" (Coutinho, 2018, p. 140).

Moreover, his reflections, which have a strong mystical component, make him a thinker of a high level of esotericism. Although he adapts some elements of Aristotle's philosophy to a new conception of the world—one that is no longer closed and finite, but open and infinite—Bruno adopts esoteric positions regarding matter and solid bodies. From the perspective of matter, he accepts an animistic view, attributing to it "the character of a living thing; it is worth noting that, for him, each celestial body is a great animal, endowed not only with sensitivity (which he attributes to all bodies, large and small) but even with intelligence (the movement of the stars would be regulated by this intelligence)" (Coutinho, 2018, p. 143).

Further reflecting Aristotle's influence, he emphasizes qualitative analysis and even claims that natural bodies influence each other reciprocally through *empathy*, a specific sentiment of living beings (Coutinho, 2018, p. 143, emphasis in the original). Giordano Bruno does not break away from Aristotle's theory of causes; he still attributes a final cause to natural movements, assigning evaluative judgments to movement: "the stars move

because they are commanded by a purpose, that is, because movement is better than rest” (Coutinho, 2018, p. 143).

However, his importance lies in using the scientific developments of his time to make ontological generalizations about the Universe, nature, and humanity.

It is through this long, multi-century process of contradictory developments spanning from Antiquity to the Renaissance that the foundations for the birth of modern science as we know it today were established. However, it is not possible to draw a rigid line between the thinkers of the European Renaissance and those of the modern era. For example, we will later discuss other thinkers considered Renaissance figures, but who played much more significant roles in the scientific revolution of modernity. Therefore, the expositional and chronological order we have chosen is merely conventional.

There is no doubt that there were both ruptures and continuities, but, to paraphrase Coutinho (2018, p. 125), “[t]here is no barrier between Renaissance and ‘modern’ thinkers.” What truly matters is that these great figures belong to the same horizon: in their own ways, they contributed to the construction of a new worldview and the birth of modern science.

3
THE SCIENTIFIC REVOLUTION AND THE BIRTH OF MODERN SCIENCE

Although we have discussed only a few Renaissance thinkers in the previous section, the line separating them from the great figures of the scientific revolution is quite thin. This is for a very simple reason: some of the key figures from the early period of modern science are themselves Renaissance figures.

By not drawing a strict boundary between the Renaissance and modernity, we are merely illustrating the elements of rupture and continuity between pre-modern and modern worldviews. As will be shown below, for example, the Copernican model includes elements from two major scientific traditions. It is possible to identify elements from antiquity, as well as features that characterize it as modern. The opposition between these periods is, therefore, an illusion: "Copernicus is neither an ancient nor a modern but rather a Renaissance astronomer in whose work the two traditions merge" (Kuhn, 1995, p. 182).

Indeed, the so-called Scientific Revolution takes place precisely between the twilight of the Renaissance and the dawn of Modernity. As Henry (2002) states, the Scientific Revolution is the name given to the period in European history that first establishes the conceptual, methodological, and institutional framework of modern science as we know it today. The time-frame marking this process of formation spans from the 16th to the 18th century.

Obviously, as we have seen, this does not mean that there was no proper scientific inquiry during the pre-modern period. In fact, there was, but the term "science" at the time corresponded to what was called natural philosophy. Over time, this term underwent profound changes until it aligned more closely with our current conception of science. Therefore, "[t]he Scientific Revolution should not be seen as a revolution in science, because there was nothing like our notion of science until it began to be forged in the Scientific Revolution out of previously distinct elements" (Henry, 2002, p. 5, emphasis in the original).

The fact is that between 1500 and 1700, Western Europe experienced deep economic, social, and cultural transformations, significantly altering how the natural and social worlds should be understood, "be studied, analysed and represented, and many of these developments continue to play a significant part in modern Science" (Henry, 2002, p. 1). Interestingly, most of the major works from thinkers of this period had the word "New" as a suffix in their titles, indicating a new scientific approach to understanding reality (Henry, 2002).

However, modern science, according to Koyré (1943a, p. 333), "does not originate from earth alone. It comes, just as well, from the skies. And it is in the skies that it finds its perfection and end." We will see that, much like in pre-modern science, the key figures of the Scientific Revolution focused on the study of physics and astronomy.

Modern science and its principles emerge from the astronomical and cosmological problems of the closed, qualitatively hierarchical universe, governed by differentiated causal laws in the terrestrial and

celestial realms, as conceived in Antiquity and the Middle Ages. In contrast, modern science posits the infiniteness of the universe and the uniformity of matter, "governed and united by the identity of its fundamental laws" (Koyré, 1943a, p. 334).

It is not entirely possible, however, to attribute, as Alexandre Koyré largely does, the advancements leading to the emergence of modern science solely to the genius of the great figures of the Scientific Revolution and the primacy of purely intellectual efforts. The "geniuses" of any given era are always embedded in their respective economic, social, and cultural contexts. Thus, a comprehensive view of the broader picture surrounding the rise of modern science, under the lens of materialism, is only possible if analyzed as a whole.

A clear example of the fundamental role played by the social relations of the time in the birth of modern science can be seen in the rising commercial capitalism's need to use mathematics as an important accounting tool.

Hadden (1994), for instance, argues that the widespread use of mathematics during the transition to modernity is largely tied to the mercantile generalization of the time, the development of early capitalism, the great voyages, and the practical need for quantitative methods. This phenomenon created an environment conducive to the mathematization of the world and increased the prestige of the natural philosophers of the era.

Even though the Aristotelian scientific hegemony had been challenged in various ways by the previously mentioned authors, it was only with the formulation of a heliocentric system that ancient science received a significant blow.

3.1 The Revolution Begun: Copernicus, Kepler, Bacon

The publication of *De revolutionibus orbium coelestium* (*On the Revolutions of the Celestial Spheres*) in 1543 by the Polish astronomer Nicolaus Copernicus (1473–1543) was, according to Kuhn (1985, p. 134), the beginning of a revolution that "inaugurates the upheaval in astronomical and cosmological thought," marking the emergence of a worldview based on heliocentrism.

Heliocentrism was one of the greatest challenges to Aristotelian science and the geocentric model, as it displaced the Earth from the center of the universe and placed the Sun in its stead, while simultaneously affirming the Earth's mobility. "According to Copernicus, the Sun came to occupy the center of the universe, while the Earth and the other planets revolved around it". (Porto, 2008, p. 4).

Figure 6 - Nicolaus Copernicus (1473–1543).

According to Saliba (2007), Copernicus was greatly influenced by Islamic astronomers. The construction of the heliocentric model was only possible due to the precision of the calculations of celestial orbits made by these Islamic thinkers. For instance, Copernicus frequently refers to "mathematicians," attributing this term to Islamic scholars. The greatest influence, however, came from al-Tūsī, previously

mentioned, who developed an alternative to Ptolemy’s epicycles to explain celestial orbits.

Although Copernicus made fundamental objections to the Greek geocentric model, he still shared many of its principles. First, he continued to conceive of a “finite universe, enclosed by spheres, where the planets followed perfect circular orbits” (Porto, 2008, p. 4). Moreover, Copernican cosmology still relied on value attributions: “it seemed irrational to move such a large body like the Sun, rather than a much smaller one like the Earth” (Porto, 2008, p. 4). In addition, by placing the Sun at the center of the universe, Copernicus argued that it was a celestial body of superior nobility, as it was the source of light and life.

In formulating a mathematically rigorous heliocentric model, Copernicus broke away from Aristotle's idea of a division between the terrestrial and lunar worlds. “By removing the earth from the centre of the universe, Copernicus compromised the notions of ‘up’ and ‘down’ which essentially defined sublunar natural motions” (Henry, 2002, p. 21).

According to Kuhn (1985, p. 135), *De revolutionibus orbium coelestium* produced “a fundamentally new approach to planetary astronomy, the first accurate and simple solution of the problem of the planets, and ultimately, with other fibers added to the pattern, a new cosmology.” More than that, unlike his predecessors who speculatively asserted Earth's mobility, like Nicholas of Cusa, Copernicus built his heliocentric model based on mathematical proofs: “mathematics distinguish him from his predecessors, and it

was in part because of the mathematics that his work inaugurated a revolution as theirs had not” (Kuhn, 1995, p. 144).

However, Copernicus's contribution wasn't about developing new mathematical solutions for the problem of celestial orbits. Instead, it involved the systematic application of mathematical knowledge to explain certain phenomena. This distinction sets him apart, for instance, from the qualitative understanding of the universe that prevailed in antiquity, and it marks a crucial starting point for the mathematization of science (Kuhn, 1995).

The mathematization of reality was a fundamental factor in the development of modern science. The pivotal point, however, is that the issues within the geocentric model, which “contributed to its increasing degree of artificiality and obscurity, were more naturally explained” (Porto, 2008, p. 4) by Copernicus. For example, “the irregularities observed in planetary movements were now attributed to the fact that these movements were being observed from the point of view of Earth, which itself was in motion” (Porto, 2008, p. 4). However, Copernican heliocentrism was not immediately accepted[1] only after a long period of loss of Aristotelian hegemony will it be universally accepted.

[1] For example, the Danish astronomer Tycho Brahe (1546–1601) resisted accepting Copernican formulations.

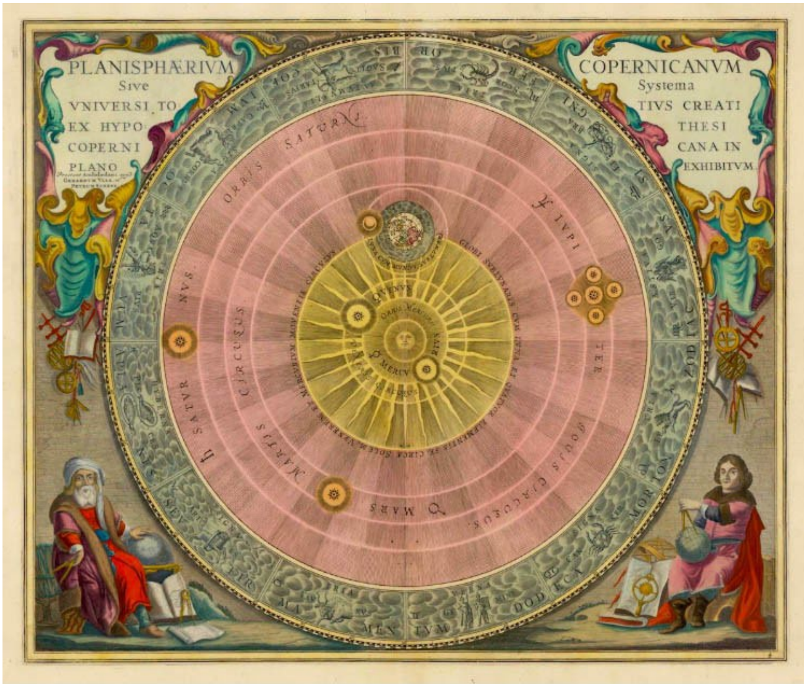

Figure 7 – Heliocentric System.
Source: Harmonia Macrocosmica (Cellarius, 1660).

Johannes Kepler (1571-1630), undoubtedly the greatest Copernican astronomer (Henry, 2002, p. 20), envisioned in Copernicus's heliocentric system something much deeper than merely contesting the geocentric system; he also saw the path toward establishing a new theoretical framework to mathematically describe an ordered and harmonious Universe (Porto, 2008, p. 5). Furthermore, Kepler took a decisive step and proclaimed the unity of matter in the whole universe (Koyré, 1943a, p. 345).

With the publication of *Astronomia Nova* in 1609, Kepler made another important move in challenging Greek cosmology and creating the scientific discourse of modernity. Based on Tycho

Brahe's astronomical calculations, Kepler argued that the evidence pointed to the incompatibility of the idea of perfect circles for explaining celestial orbits. The available data of the time indicated an elliptical mathematical shape for planetary orbits (Porto, 2008).

Figure 8 - Johannes Kepler (1571-1630).

From the elliptical orbit, according to Koyré (1965, p. 8), Kepler formulated his laws of celestial motions and thus destroyed the orbs and spheres that encompassed the world and held it together. This decisive step in demonstrating that planetary orbits do not conform to the shapes based on the perfect solids of antiquity undermined the idea of natural movements. The elliptical shape required a new explanation for motion that was not Aristotelian: to explain this orbital shape, Kepler proposed that the Sun be a source of motion in the Universe (Porto, 2008, p. 5).

Kepler was inspired by the work of English physicist William Gilbert (1544-1603), the discoverer of the Earth's magnetism, to argue that all celestial bodies possessed magnetic attraction, with the Sun serving as the driving force behind the interaction between the magnetisms of the involved bodies (Porto, 2008, p. 5). This magnetic force would be responsible for the elliptical shape of planetary orbits. This explanatory framework eliminated any external factor necessary to set a planetary system in motion. Thus, the first idea of the planetary system emerged as a self-governing system, requiring no reference to causes outside the system itself (Porto, 2008, p. 5).

Another important advancement in the development of modern science is the introduction, for the first time in history, of the idea of mutual attraction between bodies. On one hand, Kepler argues that the concept of gravity must be based on the idea of mutual attraction; that is, the Earth attracts any object, just as that object attracts the Earth. Similarly, the Earth and the Moon attract each

other, and this is the mechanism that explains their continuous separation.

As Henry (2002, p. 20) indicates, Kepler goes beyond his predecessors by proposing a physical explanation for celestial orbits:

> [H]e not only discovered that the planets take elliptical paths around the sun (which is situated at one focus of the ellipse), and that the speed of the planet varied continuously, increasing as the planet approached nearer to the sun, decreasing as it receded, but he also proposed a physical explanation for those movements. Indeed, the full title of his *New Astronomy* indicated that it was 'based on a theory of causes' to provide a 'celestial physics'.

On the other hand, in Kepler, we can see Aristotelian remnants when he claimed that the mutual attraction of bodies only pertains to "kinship." For example, the Earth would have a kinship with the Moon but not with the other planets and celestial bodies. In other words, "there was still in Kepler's thought an Aristotelian element, manifested, in this case, in the physical role, to some extent determining, attributed to the essences (natures) of bodies (the notion of affinity or kinship)" (Porto, 2008, p. 5). It is only with Newtonian synthesis that the theory of gravitation reaches its peak.

The Englishman Francis Bacon (1561 – 1625) took it upon himself to elevate the condition of vita activa during this period: while it became possible to construct a new rationality to understand the laws of nature as objective, it is with Bacon that this rationality attains an instrumental dimension of dominating nature. A fundamental trait for the formation of the new capitalist society in the making, the domination of nature through instrumental means is one of the cornerstones of Baconian thought.

The synthesis of instrumental rationality in Bacon's thinking can be seen in his famous phrase *knowledge is power*, “understood as power in the capacity to dominate nature” (Coutinho, 2018, p. 145).

Unlike the feudal economic system, emerging capitalism necessarily relies on instrumental means that enable its continuous expansion. This is why Bacon's formulations have a very close relationship with their origins. The main Renaissance thinkers were predominantly Italian, a nation that held a significant position in commercial and banking capital at the time. In England, however, manufacturing was already developing, marking the initial experiments of future industrialization. This fundamental point underscores Bacon's imperative desire to develop an instrumental rationality for dominating nature in the name of human progress.

Philosophy and science play a role in helping humans understand and control nature, putting it at the service of humanity. According to Bacon, “nature, in order to be dominated, must be obeyed: that is, we must know exactly how nature works so that we can use it to our advantage” (Coutinho, 2018, p. 145).

Figure 9 - Francis Bacon (1561–1625).

In addition to the role of subordinating nature to scientific knowledge, Bacon also argues that there are no final causes in nature, thus breaking with Aristotelian cause theory. This break complements the position of nature's domination by science: without final causes in nature, it becomes possible to control it by uncovering its mechanisms of operation. In this sense, Bacon

"contrary to the Aristotelian tradition of medieval scholasticism, (...) insists that nature knows no final causes, only efficient or material causes" (Coutinho, 2018, p. 145).

As we can see, this period is characterized by the suffix "new" in the significant works that defined the era. In Bacon's *New Atlantis*, he does not present us with a social utopia, but rather a utopia of technology, as he describes a society where technical and technological development is synonymous with human progress[2]. "This clearly illustrates the nature of the new rationality proposed by Bacon: a rationality at the service of creating new machines, technical instruments capable of increasingly subjecting nature to the designs of man" (Coutinho, 2018, p. 146).

During the transition to modernity and capitalism, there is a clear attempt to conceive imaginary societies "capable of preventing the obvious human devastations that capitalism, in its phase of primitive accumulation, was introducing into the world" (Coutinho, 2018, p. 145). This is evident in the literature of Miguel de Cervantes (1547-1616) in *Don Quixote*, as well as in works based on utopias, originating with Thomas More (1478-1535).

To establish such a society, it was necessary to create a new logic and a new method capable of rationally understanding how nature effectively operated. In *Novum Organum*[3], Bacon proposes a new method for analyzing nature. In his writings, he outlines "a new method that, allowing for an effective understanding of nature,

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2 The remark made by Coutinho (2018, p. 146) is relevant here: "It should be noted that in Bacon, as in much of bourgeois thought, progress is identified and reduced to technical progress".

3 The name of the treatise is suggestive: it stands in contrast to Aristotle's logical writings in the book *Organon*.

leads men to obey its laws and, in this way, become capable of using them for their own progress" (Coutinho, 2018, p. 146).

This new logic was based on an inductive conception, in contrast to Aristotle's deductive logic. According to Henry (2002, p. 36), Bacon believed that prior theories and hypotheses would lead the investigator to misleading understandings. By gathering and understanding all the facts, Bacon "believed that once all the facts about any given topic were available for easy scrutiny (...), an explanatory theory would spontaneously emerge." The fundamental aspect of Bacon's approach is that, starting from experience and after carefully examining the facts, one can arrive at general hypotheses (Coutinho, 2018, p. 147).

The proposition that knowledge begins with experience and that general propositions can be inferred from it is what connects Bacon to several foundational thinkers of modern science. However, Bacon's weakness in becoming one of the most prominent figures of the Scientific Revolution lies in the little importance he assigns to mathematics and controlled experiments: "therefore, his induction is poor and imprecise (...) and, moreover, Bacon does not foresee artificial experiments" (Coutinho, 2018, p. 147).

According to Henry (2002, p. 36), it is only in Galileo's formulations that the idea of the modern experiment takes shape: "[i]n spite of his reputation as a founder of the experimental method, what Bacon described (...) was far removed from, say, the more modern-looking experiments with inclined planes devised by Galileo to investigate the behavior of falling bodies."

3.2 The Birth of Modern Science: Galileo, Descartes, Newton

It was only with Galileo Galilei that modern science began to take its definitive shape. Galileo, "to whom modern science owes perhaps more than to any other man," in the words of Koyré (1957, p. 95), is undoubtedly the one who will bring about the fundamental changes necessary to understand reality as a physical system, characterized by matter, movement, and space that differ from the ancient period. More than that, Galileo will deal the final blow to the Aristotelian worldview. That is, "he marshalls his arguments and prepares for the final assault on Aristotelianism" (Koyré, 1943a, p. 345).

The figure of Galileo, in Koyré's words (1943b, p. 400):

> (...) is indissolubly linked with the scientific revolution of the sixteenth century, one of the profoundest, if not the most profound, revolution of human thought since the invention of the Cosmos by Greek thought: a revolution which implies a radical intellectual "mutation", of which modern physical science is at once the expression and the fruit.

Galileo improved various scientific instruments such as lenses, compasses, and thermometers. He also enhanced an instrument that was initially developed to ensure the anticipation of maritime invasions by foreigners for the Venetians, but which, when pointed to the sky, produced a definitive upheaval in the closed cosmos, formed by perfect spheres in harmony as understood by the Greeks: the telescope.

Figure 10 - Galileo Galilei (1564-1642).

With the publication of *Sidereus Nuncius* (*The Starry Messenger*) in 1610, Galileo presented his early astronomical discoveries to the Italian public for the first time: “Great things, indeed, are what I propose in this small treatise for examination and contemplation by all who study nature” (Galileo, 2010, p. 151).

By pointing the telescope at the heavens, Galileo discovered that the celestial world was not that of the Greeks: he found that celestial bodies did not have a perfect circular shape but were spherical and irregular; that the Moon did not appear to be made of a material different (Ether) from that of the Earth, possessing craters, valleys, and mountains; that Jupiter has four moons in its orbit; that the planetary system is not supported by crystalline spheres; that the Sun has spots; that there are countless suns and stars, etc. In summary, through empirical observation, Galileo challenged nearly two thousand years of geocentric cosmological hegemony.

However, it is in *Dialogo sopra i due massimi sistemi del mondo* (*Dialogue Concerning the Two Chief World Systems*), published in 1632, that Galileo's formulations gain greater theoretical and empirical density. In the *Dialogue*, Galileo (2011, p. 91-92) states that one of his objectives is “to show that all feasible experiments on Earth are insufficient resources to conclude its mobility, but can be adapted indifferently to both the moving Earth and the Earth at rest.” Furthermore, he asserts that he investigated “celestial phenomena, reinforcing the Copernican hypothesis as if it were absolutely victorious, adding new investigations that serve, however, to facilitate astronomy and not out of necessity of nature” (Galilei, 2011, p. 92).

According to Koyré (1957, p. 97), Galileo's *Dialogue* is a work “intended for the ‘general reader,’ a book which aims at the destruction of the Aristotelian world-view in favor of that of Copernicus.” That is, the refutation of geocentrism and the proof of heliocentrism.

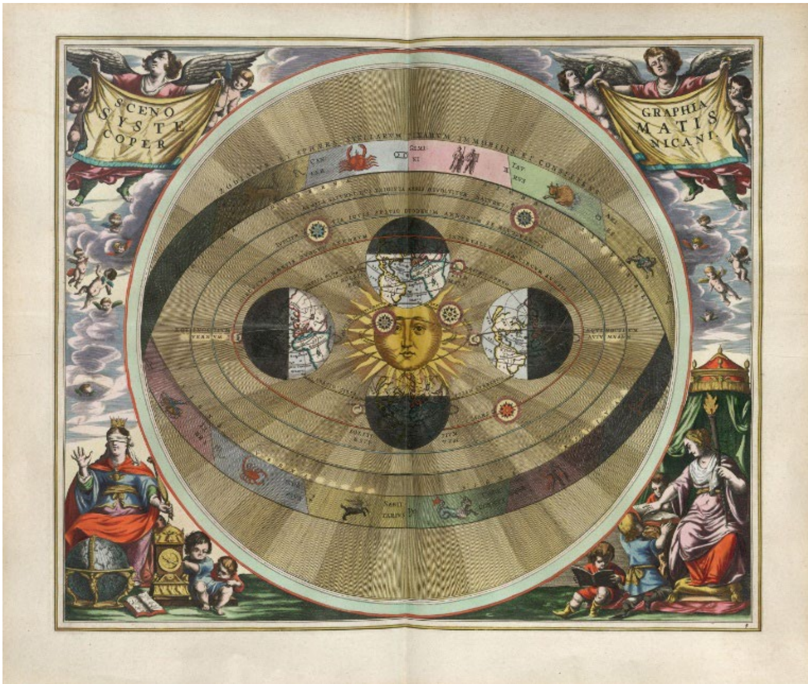

Figure 11 – Copernican System.
Source: Harmonia Macrocosmica (Cellarius, 1660).

Although Galileo's predecessors had somewhat articulated the need for the mathematization of science as a means to ensure analytical rigor, his position marks a novelty: the *systematic* use of mathematics to understand phenomena scientifically.

It is no coincidence that Galileo (1983, p. 46) states that the natural world is a book written in geometric characters. It is the task of natural philosophy, or rather, science, to unveil its secrets:

> Philosophy is written in this great book that continually unfolds before our eyes (that is, the universe), which cannot be understood before we learn the language and become familiar with the characters in which it is written. It is written in the language of mathematics, and the characters are triangles, circles, and other

> geometric figures, without which it is impossible to understand the words in a human sense; without them, we wander lost in a dark labyrinth.

Thus, as Koyré (1943a, p. 347) asserts, "[f]undamental laws of motion (and of rest), laws that determine the spatio-temporal behavior of material bodies, are laws of a mathematical nature. Of the same nature as those which govern relations and laws of figures and of numbers." In other words, mathematics is the language of the Universe, and therefore also of science in the quest to uncover its mechanisms of operation.

If mathematics is the language of nature, then science aims to develop that language to "discover the laws that allow us to understand phenomena and their relationships in mathematical terms" (Coutinho, 2018, p. 150). The general laws of the physical world are comprehensible to the human mind through (1) empirical observation and its corresponding (2) analysis by human reason.

The systematic use of mathematical instrumentalism was not only designated to explain astronomical and physical phenomena, but it also played a central role in the new society that was emerging. One can identify that the expansion of trade and the formation of a global market through the colonization of the world gave mathematical techniques a fundamental prominence. This meant that "practical mathematical techniques like navigation, surveying, and cartography came to be seen as much more important, attracting the interest of some leading intellectuals and enabling some lowly practitioners to raise their social and intellectual status" (Henry, 2002, p. 22).

Another fundamental point for the birth of modern science is the possibility of abstracting the qualitative determinations of the object. While qualitative analysis was the focal point in ancient science, modern science seeks to abstract all qualities of the real: "Galileo (...) seeks to 'cleanse' the object of everything that is not mathematical or quantitative, since, for him, qualitative sensory perceptions (color, smell, etc.) would be purely subjective and have nothing to do with science" (Coutinho, 2018, p. 147).

With the attributes of mathematization of science and the elimination of the qualitative specificities of the real, Galileo constructed his experimental method, which would be fundamental for modern science. The Galilean experimentalism aims to conduct experiments isolated from disturbances in the external environment. That is, it abstracts the qualities of the objects, isolates them from the outside in controlled and artificial settings, observes the occurring facts, formulates hypotheses, conducts experiments, and then builds general theories.

Furthermore, from this path taken, it becomes possible to make global generalizations from local results. In other words, Galileo's perspective also paves the way for the establishment of reductionism as an analytical principle of science. Since it is necessary to abstract all the qualities of objects, the world presents itself as a collection of homogeneous entities. The phenomena analyzed in controlled and local experiments can therefore be universalized to any scale. In other words, the phenomenon of the experiment is valid and applicable to the entire Universe. The simplest phenomena occurring on a smaller scale in reality are, in

their aggregate, the key to understanding phenomena throughout nature (Prigogine; Stengers, 1984).

Through these steps of experimentalism, Galileo was able to realize that solid bodies with different masses, dropped from the same height in free fall, would take the same time to reach the ground, contradicting the Aristotelian assertion that bodies in free fall have different accelerations depending on their mass. From this observation, "through mathematical analyses, he formulated the theory of uniformly accelerated motion for falling bodies" (Porto, 2008, p. 5).

On the other hand, the idea of motion gains a new status, no longer being an essential transformation of the object as in Aristotelian thought, but rather a geometric translation between points in an undifferentiated and neutral space (Koyré, 1966). This new conception can be described as follows:

> [M]otion is considered as purely geometrical translation from one point to another. Motion, therefore, in no way affects the body which is endowed with it; to be in motion or to be at rest does not make any difference to, or produce a change in, the body whether in motion or at rest. The body, as such, is utterly indifferent to both. Consequently, we are unable to ascribe motion to a determined body considered in itself. A body is only in motion in its relation to some other body, which we assume to be at rest. We can, therefore, ascribe it to the one or to the other of the two bodies, *ad libitum*. All motion is relative (Koyré, 1943a, p. 336).

According to Koyré (1966), one of the cornerstones of Galileo's contribution is the formulation of the principle of inertia. It is through this principle that the contradiction between immediate human experience and the mobility of the Earth could be decisively

dismantled. Aristotelian physics proposed that every body in motion suffers a constant external force. From the principle of inertia, Galileo demonstrated that "just as a body at rest tends to remain at rest, a body in motion tends to remain in motion unless acted upon by an external agent" (Porto, 2008, p. 5).

On the other hand, the idea of inertia was also able to refute one of the strongest Aristotelian arguments for the immobility of the Earth: the problem of projectile motion. According to Aristotle, a projectile launched upward to a considerable height would inevitably fall at a point distant from the launch point, given that the Earth would have moved.

Galileo unequivocally demonstrated, through the principle of inertia, that bodies on Earth retain their motion. That is, according to Porto (2008, p. 5), Galileo was able to show "that all objects located on Earth, as well as the observers situated on it, are automatically endowed with the motion of the planet itself and, therefore, this motion would be imperceptible to any of those observers."

To be brief, Koyré (1943a, p. 337) identifies three basic conditions for the development of the principle of inertial motion from Galileo: the first is "(a) the possibility of isolating a given body from all its physical environment" (Koyré, 1943a, p. 337). Conjointly, the second concerns "(b) the conception of space which identifies it with the homogeneous, infinite space of Euclidean geometry, and (c) a conception of movement – and of rest – which considers them as states and places them on the same ontological level of being" (Koyré, 1943a, p. 337). The foundation of modern science, therefore,

"aims at the explaining of everything by 'number, figure, and motion'" (Koyré, 1943a, p. 334).

Galileo thus laid the fundamental bases for the birth of modern science and the destruction of the ancient worldview. No longer concerned with issues of value and qualities, the science that began to take shape with Galileo was focused on rationally understanding the real mechanisms at work in reality and did so through experiments that could be empirically verified, with their results organized into general theories.

Galileo's discoveries were so significant in dismantling the ancient worldview that he was persecuted and tried by the Inquisition for heresy. However, unlike Giordano Bruno, Galileo accepted the charges, renounced his major discoveries, and affirmed the truth of the geocentric worldview. He did this solely to save his life. By doing so, Galileo ensured that the Catholic Church would spare his life and that he would not become a martyr of science like Bruno.

The extraordinary weight of Galileo's figure in the development of modern science is such that it is no coincidence that the great playwright Bertolt Brecht (1898-1956) dedicated himself to writing the play *Life of Galileo*, using theater to illustrate the contradictions between one of the founding fathers of modern science and the institutions of his time (Brecht, 1991).

There is a well-known story that claims that upon leaving the inquisitorial tribunal, Galileo whispered, *Eppur si muove*, meaning that although he had claimed the immobility of the Earth before the court, the Earth moves. Perhaps this represents the most famous conflict between science and religious authority.

The French philosopher René Descartes took another decisive step in the construction of modern science. By elevating the mathematization of reality to a new level, he also systematized the mechanical conception of the Universe. As Koyré (1957) states, the world of Descartes is not that of Aristotelian thought, which is qualitatively determined with teleological explanations. Modern thinkers abandoned teleological determinism to establish mechanical determinism.

Figure 12 - René Descartes (1596-1650).

The world of immediate human experience, full of confusion and sensory error, is definitively replaced by a world of mathematics, geometrically uniform, capable of providing us with true and rigorous knowledge. In this new world, there is only space and motion, both identical to extension and space: therefore, there is nothing beyond extension (length, width, and depth) and motion in the Cartesian world.

According to Koyré (1957, p. 101), this identification results in the absolute negation of the void: "[t]he famous Cartesian identification of extension and matter (...) implies very far-reaching consequences, the first being the negation of the void, which is rejected by Descartes in a manner even more radical than by Aristotle himself."

Now, if matter is synonymous with extension in length, width, and depth, the inevitable conclusion is the physical impossibility of the void. No physical structure can lack properties and, consequently, dimensions. This is the result of equating matter and space. Furthermore, according to Koyré (1957), another important consequence of equating matter and extension is the rejection of the finitude and limitation of space and the real world.

However, Descartes does not use the word infinite but rather indefinite to characterize the Universe. Thus, "[t]here is no longer any need to discuss the question whether fixed stars are big or small, far or near" (Koyré, 1957, p. 154), but these questions become merely problems of calculation and observation.

Henry (2002, p. 71), however, argues that the identification between matter and extension pertains to the unification of

mathematics and Cartesian physics, enabling the definition of physics as the science that studies the motion of bodies geometrically: “Based upon a unification of mathematics with physics (...) Descartes’s philosophy defined matter solely in terms of extension. This enabled him (...) to claim that physics could be based upon geometrical analysis of extended bodies in motion”.

From these considerations, ontological discussions about the constitution of the Universe gain new dimensions. Unlike pre-modern science, reality is composed of indivisible, autonomous entities that aggregate to form the structures of the world around us. According to Descartes, “Nature was rigorously ordered and impersonal, governed by Mathematics, and composed of an infinite number of particles that collided and could aggregate” (Porto, 2008, p. 6). In other words, the establishment of atomism and reductionism as foundations for the scientific investigation of reality was underway. Cartesian Universe, formed by indivisible and autonomous entities, obey certain mechanical laws of motion, and the task of the new science would be to uncover how these laws operate effectively.

The entire discussion of the ontological differentiation between a terrestrial world and a celestial world—which persisted even with Copernican formulations—is completely abandoned. The Universe is now filled with the same undifferentiated matter and follows the dictates of the same general laws of operation: “The unification and the uniformization of the universe in its contents and laws becomes a self-evident fact (...) at least if we take the term ‘world’ in its full sense” (Koyré, 1957, p. 105).

From an epistemological and methodological standpoint, Descartes was the one who enabled the widespread dissemination of the reductionist conception of scientific analysis. That is, the realization of the possibility to reduce the complexity of objects into their respective singular components, analyze them in isolation, and then reconstitute the object of analysis through aggregation.

According to Descartes, from this new conception of the world, it was necessary to "seek some other method" (Descartes, 2001, p. 22). In principle, it is fundamental, Descartes continues (2001, p. 23), to "divide each of the difficulties examined into as many parts as possible and necessary to resolve them better." The order, however, establishes that the course of thought begins "with the simplest and easiest objects to know, gradually ascending, like steps, to the knowledge of the most complex" (Descartes, 2001, p. 23).

Grounded in an atomist ontology, which conceives reality as a collection of entities with autonomous properties, the expected outcome is reductionism as a pillar of scientific analysis, since no property is lost in the process of decomposition and explanatory reduction.

The full development of the Law of Inertia enabled Descartes to formulate a mechanical conception of the Universe: "since all motion in the Universe is of mechanical origin, any deviations from their natural straight-line tendencies must be the result of collisions with other bodies" (Porto, 2008, p. 6).

Descartes more accurately formulated the principle of inertia than Galileo by understanding the linear nature of the movements of bodies. According to Porto (2008, p. 6), by conducting a thought

experiment about how a single particle would move in an infinite universe, Descartes concluded that "a body at rest would remain at rest and a body in motion would continue to move in a straight line at the same speed unless acted upon by an external agent."

Finally, Descartes' mechanical conception of the world was also applied to all domains, even to circulatory and muscular movements. Like a great machine, physical bodies would function as levers and gears: "The mechanical philosophy was also applied to the understanding of muscular movements, either by means of the mechanical analysis of the loads exerted to move the skeleton" (Henry, 2002, p. 81).

This mechanical conception of the world was also applied to the plant and animal realms:

> The mechanical philosophy was used to explain everything which previously had been explained in terms of the operations of the vegetative or animal souls – substantial forms believed to endow living creatures with the powers of reproduction, growth and nutrition (vegetative), and perception, appetites and self-motion (animal) (Henry, 2002, p. 81).

Thus, "all aspects of animal behavior can be reduced to machine-like responses to appropriate stimuli. (...) The result was a new concept of living creatures as *bêtes-machines*, which always acted in strict accordance with the laws of mechanics" (Henry, 2002, p. 81). With this, modern science was taking definitive steps. However, the synthesis of modern science would be established based on Newtonian formulations.

The synthesis of modern science reached its greatest splendor with the work of Isaac Newton. Newtonian mechanics and the theory

of universal gravitation became one of the cornerstones of modern science, given their practical and mathematically rigorous nature in solving the main astronomical and physical problems of the modern period.

As Koyré states, Newton is the ultimate expression of the Scientific Revolution that began in the sixteenth century. The newtonian synthesis of modern science encompasses a view of the world as a predictable and mechanically structured machine[4], abolished once and for all "the world of qualities and sense perception, the world of appreciation of our daily life, and to replace it by the (archimedean) universe of precision, of exact measures, of strict determination" (Koyré, 1965, p. 5). The peak of modern science with Newton, therefore, was the establishment of the investigation of reality whose assumptions are quantification, precision, accuracy, and determination (determinism).

4 To better understand the process of the "mechanization" of the world with the emergence of modern science, see the work of Dijksterhuis (1961).

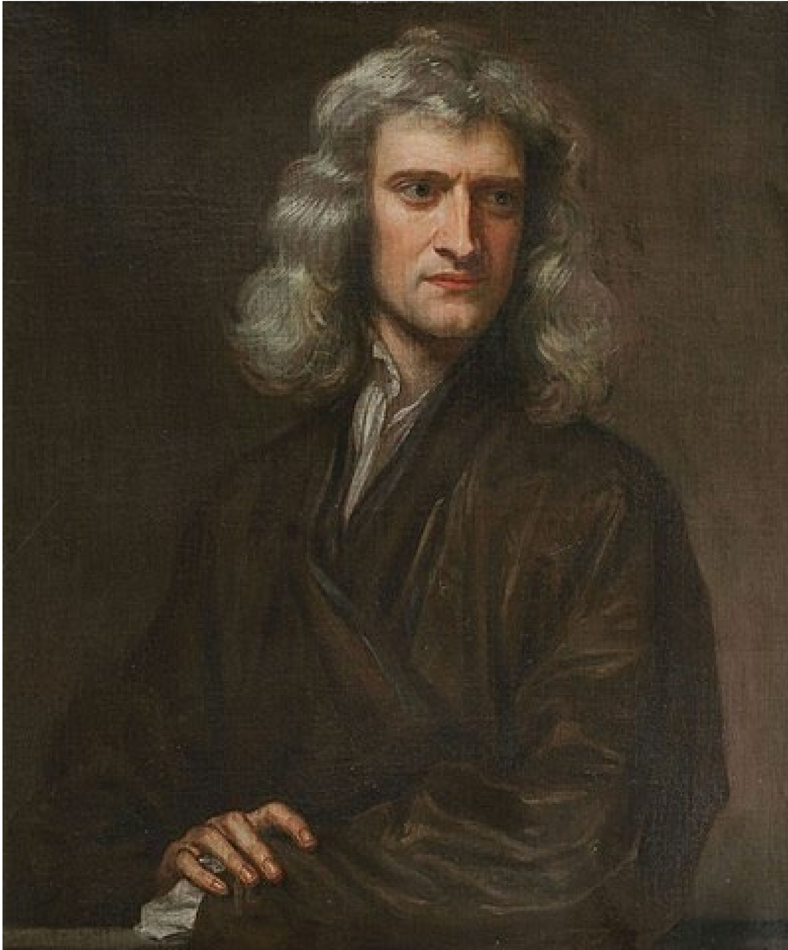

Figure 13 - Sir Isaac Newton (1642/1643-1727).

The publication of *Philosophiæ Naturalis Principia Mathematica* (*Mathematical Principles of Natural Philosophy*) in 1687 can be characterized as the culmination of modern science. Newton became the most prominent figure in scientific knowledge, representing the culmination of mechanical philosophy initiated by earlier thinkers. Or rather, in the words of Ulanowicz (2009, p. 19), "Newton

inadvertently had become the founding father of a mechanical philosophy of nature."

In *Principia*, Newton formulated the fundamental laws of motion and resolved the main problem of mechanics. The work can also be viewed, according to Henry (2002, p. 28), "as the culminating point of the mathematization of the world picture." Furthermore, "[t]he publication of Newton's *Principia* marks the completion of the trend towards the mathematization of natural philosophy which began in the sixteenth century" (Henry, 2002, p. 28).

According to Porto (2008, p. 7), Newton was able to understand that "the path described by any body is determined from the knowledge of the forces acting upon it and certain initial conditions, represented by its position and velocity at any moment." Thus, "[o]nce these elements are known, we can determine this trajectory in an absolutely unambiguous manner" (Porto, 2008, p. 7).

Through the development of integral and differential calculus[5], Newton provided modern science with the predictive capability that became one of the main foundations of mechanical scientific knowledge. What is important now, however, is that with the Newtonian synthesis, "[t]he evolution of scientific thought, initiated by Galileo and Descartes, toward the conception of a Nature described by mathematical laws thus reached its great blossoming" (Porto, 2008, p. 7).

In the Newtonian universe, there is no ontological distinction between earthly and celestial phenomena. All physical phenomena

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5 There is a controversy over who really developed calculus. At the same time, Newton and the German Gottfried Wilhelm Leibniz (1646–1716) contested the authorship of the creation of calculus concepts. For further understanding, see Hall (1980).

obey the same fundamental laws. The law of universal gravitation[6], for example, underpins the fall of bodies everywhere and at all scales. That is, according to Koyré (1965, p.), "it is the same set of laws which governs all the motions in the infinite universe: that of an apple which falls to the ground and that of the planets which move round the sun".

Let's look at the problem-solving power of the Newtonian scientific synthesis: (1) through the principle of universal gravitation, Newton solved the problem of the fall of bodies; (2) with the formulation of the three laws of motion and gravity—which states that the attraction between bodies acts "with an intensity proportional to the product of their masses and inversely proportional to the square of the distance that separates them" (Porto, 2008, p. 7) - Newtonian mechanics solved the Keplerian problem of planetary motions and projectile launches; (3) Newton resolved the issue of Kepler's elliptical orbits by stating that gravity acts as a force inversely proportional to the square of the distance between bodies, describing conic sections, and when closed, the orbits become elliptical[7]; (4) Newton explained the flattened shape of the Earth's poles through its rotation on its own axis; (5) Newton accurately

6 Prior to Newton, as previously mentioned, the idea of the principle of gravitation was already taking shape. Robert Hooke (1635–1703), for example, while conducting experiments on the trajectory of spheres, "observed that what forced the sphere to follow that trajectory was a central-type force, that is, directed toward a center of force that remained motionless" (Porto, 2008, p. 6). However, "apparently, he was not able to give his conception the appropriate mathematical development" (Porto, 2008, p. 7).

7 Hooke accused Newton of not giving him due credit in the formulation of universal gravitation. In the letters exchanged between Hooke and Newton at the end of the seventeenth century, it is evident that Hooke had stated it was possible to solve the Keplerian problem of orbits through the idea of a single force like gravity: "This fact is strikingly illustrated by the short shrift given to Robert Hooke (1635–1703) concerning his claim that Newton had the main principle of celestial mechanics from him" (Henry, 2002, p. 29).

explained the precession of the equinoxes[8] "because the Earth is flattened at the poles, the gravitational attractions produced by the Moon and the Sun would create a torque, responsible for precession" (Porto, 2008, p. 7). Finally, Newton also explained the phenomenon that causes ocean tides through the "gravitational force exerted by the Moon and, with less intensity, by the Sun" (Porto, 2008, p. 7).

With Newton, science reaches the level of the mathematical expression of nature, eliminating, in Koyré's words (1965, p. 20), "the search for causes (both physical and metaphysical)," giving way only to the mechanical description of phenomena. The Newtonian machine-world establishes an insurmountable and linear causality. The world, much like a clock, operates mechanically, having been set in motion by God[9]: "Once put in motion it ran forever. The work of creation once executed, the God of Newton (...) could rest. Like the God of Descartes and of Leibniz (...) he had nothing more to do in the world" (Koyré, 1965, p. 21).

With Newton, the principles of reductionism and mechanistic philosophy, already proposed by Galileo and Descartes, reach a new level, as the mathematical formulations that describe the laws of Nature can apparently explain phenomena at all scales. Or rather, in the words of Henry (2002, p. 28), "[o]f crucial importance for the mechanical philosophy, to which he and the majority of his contemporaries subscribed, he demonstrated mathematically how observable macroscopic effects could be explained in terms of microscopic phenomena".

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8 The motion that the Earth performs on its own axis is similar to that of a spinning top.

9 Although Newton was the highest expression of modern science, he shared deep religious beliefs (Koyré, 1965).

On one hand, Newton solved a significant number of scientific problems that had persisted for centuries with the development of the laws of mechanics and gravity. On the other hand, the principle of universal gravitation did not provide an explanation of what gravity actually was. For this reason, Leibniz, for example, dismissed Newton's gravity as a "scholastic occult quality" (Henry, 2002, p. 75). However, Newton provided the mathematically formal framework for how gravity acted in Nature. The fundamental issue was the explanatory power of a vast array of problems.

Through this long process of the constitution of modern science, which occurs alongside the emergence of capitalist society in its initial phase, it is not an exaggeration to assert that this revolution was perhaps one of the most significant that humanity has ever witnessed. Friedrich Engels's (1820–1895) characterization of this revolutionary period is extremely valuable and shows us how the geniuses of that time were always embedded in their respective social contexts:

> This was the greatest progressive revolution that humanity had ever known; it was a time that demanded giants and forged giants through the strength of thought, passion, and character, as well as through universality and erudition. One can say everything about the men who laid the foundations of the current bourgeois domination, but never that they suffered from bourgeois limitations. On the contrary: they were all, to a greater or lesser extent, imbued with the adventurous spirit inherent to the era. [...] The heroes of that time were not yet enslaved by the division of labor, which imparts to men, as we can observe in many of their successors, a limited and one-sided character. What most characterizes these heroes is that almost all of them fully engaged with the problems of their time, actively participated in political

> struggles, aligned with one party or another, and fought—some with words and pen, others with weapons, and still others with both (Engels, 2000, p. 16).

What originated from this multi-century process of the constitution of modern science in Western Europe, in which these great figures of universal history are embedded, is a new ontological, epistemological, and methodological stance for investigating reality. In the modern period, "man separates himself from nature as the differentiated natural being that will dominate it" (Prado, 2011, p. 89).

In this new socio-historical stage of humanity, Nature "comes to be seen as a disenchanted world that exists independently of man and operates according to its own laws, which are independent of his will and consciousness" (Prado, 2011, pp. 89-90). It is now the task of human beings to understand these laws "through notions such as mass, force, space, velocity, etc., translating the observable relationships between phenomena" (Prado, 2011, p. 90).

On one hand, as Koyré explains, there is the dissolution of the qualitatively structured, hierarchized, and ontologically differentiated Universe into two worlds with different laws, giving rise to "an open, indefinite and even infinite universe, united and governed by the same universal laws" (Koyré, 1943b, p. 404). On the other hand, the differentiation between Heaven and Earth is abandoned, and "all things are on the same level of Being. The laws of Heaven and the laws of Earth are merged together" (Koyré, 1943b, p. 404). All scientific investigation in the modern period is premised on the abandonment of axiomatic considerations based on perfection, purpose, harmony, and value. From this, "[i]t is in this

new Universe, in this new world of a geometry made real, that the laws of classical physics are valid and find their application" (Koyré, 1943b, p. 404).

This new stance for investigating reality in the modern period is distinguished from Antiquity for several reasons. First, by adopting mathematics as the universal language that expresses the causal mechanisms of reality, abandoning the qualitative principles of Aristotelianism: "Nature not only would be written in a mathematical language that can be deciphered by experimentation, but there would actually exist only one such language" (Prigogine; Stengers, 1984, p. 44).

Second, the abstraction of the qualities of objects imposes the proposition of an undifferentiated and neutral space, capable of being abstractly represented by geometric characters, in contrast to the idea of a hierarchically ordered Cosmos from Antiquity. Third, the adoption of the notion of motion solely as translation in physical space, in opposition to Aristotle's theory, which understood motion as a change in the object itself, and the abandonment of Aristotle's theory of causes in favor of the mechanistic conception of causality, determined only by an external force (Porto, 2009).

It is possible to identify that the general principles of this scientific inquiry are grounded in atomism, reductionism, and determinism. This science, commonly referred to as classical, which emerges with the rise of modernity, conceives reality as a vast machine that is complex, stable, and predictable. This ontological attribution of reality finds its greatest expression in the atomistic conception of the world.

The different objects of the material world are thus merely differentiated combinations of atoms. The combinations of atoms occur "through mechanical fittings associated with their shapes or by the simple circumstantial juxtaposition, like the 'entrapment' of one atom by a group of others" (Porto, 2013, p. 3). The successive collisions between them would therefore explain their reorganization in the formation of new material structures.

Modern atomism, as a general ontology, thus seeks to understand reality as a collection of autonomous and independent entities. Such entities possess fixed qualities that do not depend on their relationships with other entities. They are petrified parts in their properties and autonomous qualities that, in aggregate, explain the whole. From a physics perspective, therefore, any system is reduced to the different combinations and movements of elements with permanent and homogeneous properties and qualities. From a social perspective, as we will see, it is grounded in conceiving society as a collection of independent individuals with permanent and immutable properties and qualities that relate only externally (Hodgson, 1993).

In addition to atomism, a second fundamental principle supporting this scientific inquiry is reductionism. From the atomistic worldview, it is understood that a system is formed by autonomous components that, when combined, explain phenomena through aggregation. That is, through microscopic analysis, it would be possible to explain macroscopic phenomena. Ulanowicz (2009, p. 22) argues that “[n]ot only did this assumption entail the belief that

there exist fundamental, unchanging, smallest material units, but also that these units could be built up and taken apart again."

Reductionism is both an ontological and epistemological thesis. The ontological reduction claims that the aggregation of the properties of the parts constitutes the foundation of the properties of the whole, without the interrelations and connections producing properties that are differentiated from those of the parts in isolation. As an epistemological thesis, it asserts that it is possible to understand the dynamics of the whole from the dynamics of the parts. In other words, "in breaking a system into subunits, nothing of essence is thereby lost" (Ulanowicz, 2009, p. 22).

Causality, therefore, has a mechanical and linear character of the type "if...then." The occurrence of an event α has as its unidirectional consequence β, established under certain initial conditions. The scientific law, in this case, is the deduction of the constant empirical regularity of that event. On the other hand, as Prigogine (2002, p. 11) argues, scientific law gains deterministic status.

After Newton, determinism reached its peak with the Frenchman Pierre-Simon Laplace (1749 – 1827). Influenced by Newtonian mechanics, Laplace established that the laws of mechanics determine the behavior of particles; thus, all natural and/or social phenomena can be fully explained by the existence of necessary connections between two states of the world in a cause-and-effect relationship, established by the laws of mechanics.

From an ontological perspective, determinism presents itself as a thesis concerning the very structure of reality. That is,

"determinism is a doctrine about the nature of the world" (Earman, 1986, p. 20) and proposes the existence of an absolute necessity relationship between two states of the world: a preceding event necessarily and absolutely leads to a subsequent event. On the other hand, the relationship between these two states of the world is univocal and linear: a single preceding event completely leads to another single subsequent event. From this deterministic viewpoint, "given the way things are now, the future can't be other than it will be" (Earman, 1986, p. 18).

From an epistemological standpoint, modern determinism presents itself as the capacity of knowledge to predict the future. If ontologically reality is deterministic with respect to two events, with the subsequent event being univocally, linearly, and exhaustively caused by the preceding event, it epistemologically asserts that accurate predictions about the future can be made (Earman, 1986).

Ulanowicz (2009, p. 23) thus states that "[t]his means that nature is *deterministic* – given precise initial conditions, the future (and past) states of a system can be specified with arbitrary precision." If we have knowledge of the initial positions of the particles, "in the universe at a single instant could invoke Newtonian-like dynamics to predict all future events and/or hindcast all of history" (Ulanowicz, 2009, p. 23).

The ability to solve many practical problems and the establishment of mechanical philosophy as a worldview led to the rapid hegemonic establishment of principles governing this form of scientific thought. In this way, modern determinism quickly became the common ground for scientific formulations across all levels of

reality. By the end of the 19th century, determinism became a scientifically well-founded view of the universe on all levels: physical, biological, psychological, and social.

This modern scientific approach thus establishes itself as a form of knowledge aimed at understanding reality as a collection of autonomous, independent individual entities that, when combined, form macroscopic structures. These structures, in turn, are fully explainable scientifically by the immutable properties of the individual entities that compose them. The laws governing the behavior of these entities are derived from empirical regularities observed in events driven by an external, linear, and unambiguous causality. Although this perspective was initially established within the natural sciences, it quickly permeated the social sciences to explain human behavior and societal phenomena. This position would only be definitively challenged with the advent of complexity science throughout the 20th century.

CONCLUSIONS

Aristotle's thought remained hegemonic for centuries, serving as the primary explanation of reality. Aristotelian science maintained an ontological duality between the earthly and celestial worlds. Its science was qualitative rather than mathematical. It explained motion through the theory of violent movements, proposed the immobility of the Earth, and upheld the geocentric model. It had a multicausal approach to causality, among other aspects.

It took centuries of criticism and confrontations, first with Islamic thinkers and later with the thinkers of the European Renaissance, for Aristotle's thought to finally be refuted and replaced by modern scientific thought. The Scientific Revolution marked the birth of modern science, where the ontological and epistemological elements of modern thought permanently replaced pre-modern science. Ontological monism, the systematic use of mathematics, experiments, and measurement instruments allowed for a radically different investigation of reality.

The new world that emerged in the modern period was no longer that of Classical Antiquity. From geocentrism to heliocentrism; from dualism to ontological monism; from qualitative to quantitative science; from holism to atomism and reductionism; from multicausalism to efficient causality and determinism. All these elements, which great figures like Galileo,

Descartes, and Newton helped to construct, provided the necessary foundation for building a new worldview.

This worldview is expressed in Newton's conception of a clockwork universe, characterized by stability, predictability, and certainty of knowledge. As we have demonstrated, analyzing this evolution in the history of science, focusing on the ontological elements of worldviews, has given us a comprehensive and possibly richer perspective on this process.

The establishment of the principles of classical science provided humanity with a colossal amount of knowledge about the natural, biological, and social realities. However, it began to be heavily criticized starting in the 20th century. This criticism has led to the rise of complexity science, whose foundations seek to transition from atomism to systemic thinking, from reductionism to emergentism, and from determinism to non-linear causality. This issue may well be developed in future works.

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This book is an introductory guide to understanding a centuries-old and complex phenomenon: the transition from pre-modern science to the establishment of scientific thought in the early stages of modernity. This process, as we know, is neither linear nor peaceful. It is, above all, a turbulent phenomenon, marked by intense debates and clashes. All of this revolves around a question humanity has pondered since its beginnings: how can we coherently explain the reality around us?

To answer this question, modern thinkers had to direct their efforts against Aristotle. This was because the Greek philosopher offered the most comprehensive and coherent explanation of the world, one that remained dominant for over eighteen centuries. The process of refuting Aristotle's thought took centuries to materialize, beginning with the fundamental challenges posed by Islamic thinkers during the so-called Islamic Golden Age, between the 8th and 13th centuries.

Islamic thinkers played a crucial role in enabling European Renaissance thinkers to begin the definitive challenge to the Aristotelian worldview, paving the way for the modern Scientific Revolution.

It was within this context of everyone against Aristotle, combined with the fundamental elements of capitalism in its mercantile stage, that the Scientific Revolution flourished, laying the foundational pillars of modern science in its classical period (classical science).

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