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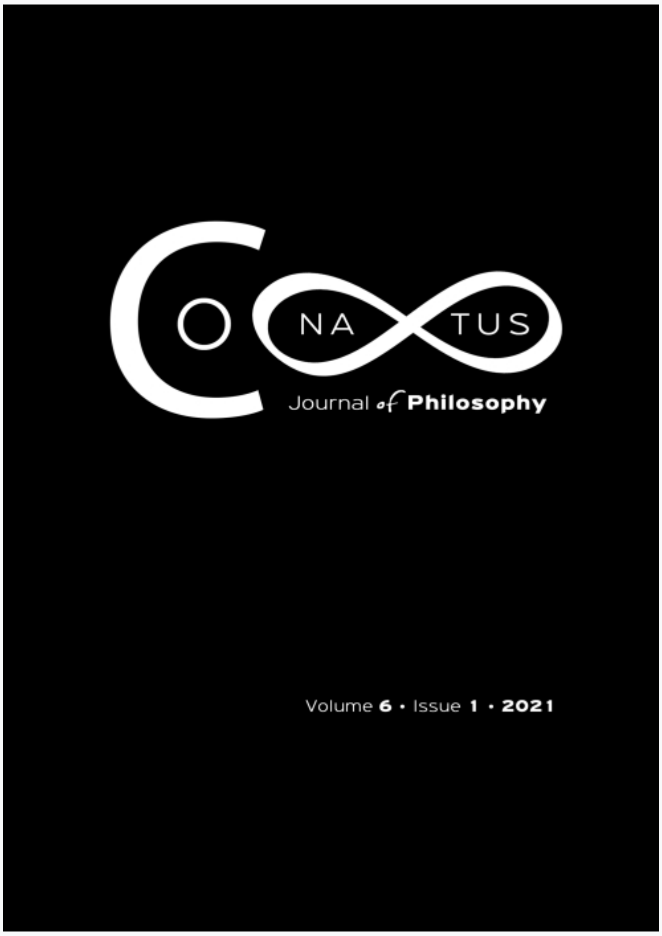

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Virginia John Grigoriadou, Frank A. Coutelieris, Kostas Theologou

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History of the Concept of Similarity in Natural Sciences

Virginia J. Grigoriadou
National Technical University of Athens, Greece
E-mail address: virgi.grigoriadou@gmail.com
ORCID iD: http://orcid.org/0000-0002-0940-1922

Frank A. Coutelieris
University of Patras, Greece
E-mail address: fcoutelieris@upatras.gr
ORCID iD: http://orcid.org/0000-0002-5998-2235

Kostas Theologou
National Technical University of Athens, Greece
E-mail address: cstheol@central.ntua.gr
ORCID iD: https://orcid.org/0000-0002-3883-601X

Abstract

The concept of similarity has been discussed by many scientists and philosophers since ancient times. Thales of Miletus, Euclid, Aristotle, Galileo, Newton, Edgar Buckingham, and the modern philosopher of science Susan G. Sterrett are examples of intellectuals who perceived and examined the concept of similarity, while many scientists incorporated it in their scientific methodology. The wide range and variety of definitions of similarity could result in confusion regarding the meaning of the concept, the role the similarity mechanism plays in scientific methodology, and the identification of scientific fields to which similarity could be applied. The main aim of this paper was to enhance the understanding of the notion of similarity. To this end, we examined the historical evolution of the concept of similarity and the utilization of the mechanism of similarity in various eras of human intellectual activity, ranging from antiquity to the present day. In this context, the research hypothesis we investigated was the existence of specific and distinct stages of evolution within the long history of the concept of similarity in parallel with the evolution of scientific thought. A core question that motivated our work was when and under which conditions did the transition from the "technocratic" utilization of similarity (i.e., the use of similarity as a solution for practical problems) to its theoretical documentation and its conscious and systematic use as a significant experimental tool occurred. Another important question examined was whether there was a certain era that favored the development of the concept of similarity more than other historical periods. In order to address this hypothesis and respond to these questions, we sought to trace the evolution of conceptualizing and using similarity in different spatial and temporal contexts, formed by the corresponding historical, institutional, religious, and social conditions as well as the characteristics of the scientific methodology established during the period the similarity concept evolved.

Keywords: *similarity; similar systems; analogy; scientific models*

I. Introduction

The mechanism of similarity is widely used in modern scientific methodology that is employed during the design of natural science experiments. The concept of similarity is characterized by a long historical evolution, which unfolds in parallel with the historical evolution of scientific thought from antiquity to current years. A significant number of philosophers and scientists from different scientific fields have approached the concept of similarity, which resulted in the existence of a wide range of definitions of the notion of similarity. In philosophy, similarity is defined as the existence of a common, similar, or analogous property or attribute between two or more objects, while in geometry it is assigned as an equal or proportional dimension.[1] In physics, similarity is considered as the ratio of specific relationships of specific physical quantities of two or more physical systems.[2] In engineering, similarity is perceived as a mechanism that operates on the basis of a set of rules, laws, principles, or mathematical relationships that are employed by the experimental technique of analogue models during the process of selecting or constructing the model and during the process of extending the conclusions from the model to the phenomenon, object, or system of interest.[3] The common ground between these different approaches of the concept of similarity is detected in the attempt to define it based on the ratio concept.

Despite the range of approaches on the concept of similarity, the study of its historical evolution reveals that during its evolutionary stages similarity is mainly associated with the fields that we nowadays collectively refer to as the natural sciences. Natural sciences have played a significant role in understanding and defining the similarity and similar system concepts and in utilizing the mechanism of similarity as a technique of experimental methodology, especially after the 17th century. The idea of similar systems is firstly detected in Galileo's experiments, while the concept of the similarity of physical systems or bodies is firstly defined by Newton in the second book

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[1] Susan G. Sterrett, "Similarity and Dimensional Analysis," in *Handbook of the Philosophy of Science*, *Volume 9: Philosophy of Technology and Engineering Sciences*, ed. Anthonie Meijers (Amsterdam: North Holland, 2010), 799-801; Susan G. Sterrett, "Physically Similar Systems: A History of the Concept," in *Springer Handbook of Model-Based Science*, eds. Lorenzo Magnani, and Tommaso Bertolotti (Cham: Springer International Publishing, 2017), 384-386.

[2] Sterrett, "Similarity and Dimensional Analysis," 800-801; Sterrett, "Physically Similar Systems," 380-384.

[3] Susan G. Sterrett, "Physical Models and Fundamental Laws: Using One Piece of the World to Tell About Another," *Mind & Society* 3, no. 1 (2002): 56-58; Susan G. Sterrett, "Models of Machines and Models of Phenomena," *International Studies in the Philosophy of Science* 20, no. 1 (2006): 69-80.

of Principia.[4] Since the beginning of the 17th century, many approaches on the concept of similarity have been recorded in the field of natural sciences.[5] At the same time, the use of the mechanism of similarity was expanding in the natural sciences and engineering. One theory that can justify the significantly extensive utilization of the mechanism of similarity in the field of natural sciences in comparison with other scientific fields is the theory of determinism, according to which everything that happens in the natural world is determined completely by previously existing causes, which necessarily lead to the same result.[6] In this context, utilizing the mechanism of similarity is more secure and effective in describing, explaining, and predicting natural phenomena than, for example, social phenomena.

Modern scientists do not exploit the mechanism of similarity by accident, unconsciously, or in an exclusively technocratic manner. On the contrary, they understand the meaning and the role of similarity in modern scientific methodology. One core question that gave rise to the present approach is the following: when, under what conditions, and how was the transition from utilizing similarity as an exclusively practical technique to its theoretical documentation and its conscious and systematic utilization as an important scientific methodological tool completed? Another question that motivated our research was whether there was a certain period that favored the development of the concept of similarity more than other periods. These two leading questions are directly related to the concern about perceiving and defining the evolution of conceptualizing and exploiting similarity as a practical technique before the advent of episteme and natural philosophy, but mainly as an experimental technique of natural sciences. The main purpose of this work was to enhance the understanding of the concept of similarity by identifying the stages of its development in correspondence with the evolutionary stages of intellectual activity.

Based on the assumption that the concept of similarity evolved alongside scientific thought and acquired its modern meaning within the scientific methodology of natural sciences over centuries, we supported that the concept of similarity went through five distinct stages of evolution. Initially, we discerned the Egyptian stage, which corresponds to a generalized way of the utilization of similarity, thereby enabling ancient Egyptians to accomplish various architectural, medicinal, and mathematical feats. The second stage dates back to the Classical era, the era of the genesis of episteme and

[4] Sterrett, "Physically Similar Systems: A History of the Concept," 381-387.

[5] Ibid., 381-387.

[6] John Earman, "Το Πρόβλημα του Ντετερμινισμού στις Φυσικές Επιστήμες," στο *Εισαγωγή στη Φιλοσοφία της Επιστήμης,* επιμ. Αριστείδης Μπαλτάς, μτφ. Πάνος Θεοδώρου, Κώστας Παγωνδιώτης, Γιώργος Φουρτούνης (Ηράκλειο: Πανεπιστημιακές Εκδόσεις Κρήτης, 1998), 319-320.

natural philosophy, when the notion of similarity appeared in philosophy, mathematics, music, and geometry and acquired increased methodological importance. The third stage is during the Dark Ages, which is characterized by the absence of experimental techniques or mechanisms, such as similarity in scientific methodology. The next stage (16^{th}-19^{th} centuries) coincides with the emergence of modern science when the concept of similarity gained new importance; during this time, similarity was expressed as a methodological idea of similar systems, mainly by Galileo who was probably the first to perceive the idea of similar systems and use it extensively in his experimental methodology, but also by Newton who was the first to define the term similar systems. Finally, the fifth stage corresponds to the period ranging from the 19^{th} century to the present day. During this period, the mechanism of similarity has been accepted as a formal methodological tool of natural sciences, and the concept of similar systems has been examined and defined by a significant number of modern scientists, with the contributions of Buckingham and Sterrett being highly important approaches. In this study, we argued that the transition from the "technocratic" utilization of similarity to its conscious utilization could be traced to the classical era stage. The transition to the systematic use of the concept of similarity as a significant experimental tool can be traced after Renaissance. Finally, we identified the period characterized by a conscious and systematized effort pertaining to the theoretical documentation of the concept of similarity and the expansion of its application to more scientific fields as starting after the 19^{th} century. Although all stages were important for the evolution of the concept of similarity, some periods favored its development and the extension of its application in several scientific fields; such a period began after the scientific revolution, when the experimental method of the 17^{th} century was introduced and the transition from natural philosophy to science was completed.

II. The origins of similarity in Ancient Egypt

Several historians of science suggest that the origins of science can be traced to ancient Egypt, after 3000 BC. The Egyptians occupied themselves systematically in the fields of mathematics, astronomy, and medicine, thereby laying the foundations for the subsequent development of these scientific fields.[7] Examples of the utilization of similarity are found in Egyptian geometry and medicine.

Egyptian geometry was primarily developed to solve practical geometrical problems. An interesting example is the construction of the pyramids of Giza,

[7] David Lindberg, *Οι Απαρχές της Δυτικής Επιστήμης* (Αθήνα: Πανεπιστημιακές Εκδόσεις Ε.Μ.Π., 2003), 19.

which leads to the following reasonable question: how did the Egyptians manage to construct pyramids similar in shape but different in size? Ancient Egyptians calculated the area of flat shapes, such as the triangle, and the volume of solids, such as the pyramid. To calculate the volume of a pyramid, they multiplied 1/3 of the base area by height.[8] Thus, it is reasonable to believe that when Egyptians were designing the pyramids, they performed mathematical calculations that allowed them to obtain geometric similarity between the different pyramids.

Another field in which ancient Egyptians used the technique of similarity was medicine. The Egyptians obtained significant achievements in the field of medicine, as evidenced by the papyruses of Ebers, Edwin Smith, and Hearst as well as the London Medical Papyrus.[9] In these papyruses, therapeutic methods, techniques, and pharmaceutical prescriptions for the treatment of illnesses, fractures, or wounds are categorized and described in detail.[10] In the Ebers Papyrus, prescriptions and medicines for various illnesses and hygiene tips are categorized in 110 columns.[11] The Edwin Smith Papyrus contains an extensive text of 48 paragraphs that describes and classifies wounds and fractures alongside with their respective treatments.[12] However, how did the Egyptian doctors compile these lists? The details on the human body and its function lead to the conclusion that this knowledge was obtained from the systematic collection and analysis of experimental data. The similarity of symptoms or medical incidents and trials of similar therapies contributed to the description, explanation, and prediction of diseases. Moreover, archaeologists believe that ancient Egyptian doctors used animals as analogue models of the human body. This belief is mainly based on wall paintings of monuments depicting doctors examining dead animals, and it is reinforced by the discovery of a large number of mummified animals in Sahara in 2018.[13] The most important source of knowledge for Ancient Egyptians was the mummification of human bodies. Studying the anatomy of bodies enabled Egyptian doctors to get to know the human body, its skeleton, and its organs. All these facts lead to the conclusion that the ancient Egyptian doctors relied heavily on similarity, both while studying the human body and when categorizing the existing knowledge about it.

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[8] Ibid., 20; Thomas Heath, *A History of Greek Mathematics, Volume 1: From Thales to Euclid* (Oxford: Clarendon Press, 1921), 122-123.

[9] Lindberg, *Οι Απαρχές της Δυτικής Επιστήμης*, 26; John F. Nunn, A*ncient Egyptian Medicine,* (Oklahoma: University of Oklahoma Press, 2002), 24-41.

[10] Lindberg, *Οι Απαρχές της Δυτικής Επιστήμης*, 26; Nunn, *Ancient Egyptian Medicine*, 24-27.

[11] Ibid., 30-31.

[12] Ibid., 25-30.

[13] BBC, "Egypt Animal Mummies Showcased at Saqqara near Cairo," accessed January 17, 2020, https://www.bbc.com/news/world-middle-east-50531808.

We do not know to what extent the concept of similarity was defined in Egyptian science; however, by studying the achievements of ancient Egyptians we can conclude that similarity had been used systematically in some cases as a means of categorizing knowledge as well as of describing, explaining, and predicting the world; whether this happened consciously or not, it was primarily aimed at solving practical problems.

III. The concept of similarity in classical antiquity (490-323 BC)

The precursor of modern science was episteme, which was born during the classical era and derived from the ancient Greek word *επιστήμη* (ἐπίστασθαι‹ ἐπίσταμαι: know, understand, be acquainted with).[14] The first to introduce the term "episteme" was Plato, while this concept was later defined more elaborately by Aristotle. Plato contrasts episteme with doxa[15] and through his dialogues he presents episteme as a condition more valuable, harder to achieve than doxa, and never false on contrary to doxa.[16] According to many intellectuals, Plato's concept of episteme resembles the meaning of knowledge; according to others, it refers to the process of understanding. In Plato's dialogue *Theaetetus*, episteme is defined as a true doxa with a logos:

ἔστιν οὖν ἐπιστήμη δόξα ἀληθής μετά λόγου,

while in his *Republic*, Plato claims through Socrates that:

episteme's object is what is.[17]

Perceiving Plato's episteme as a process of understanding is probably a more substantial approach; however, if we accept this approach, we are faced with an important question: what is the possibility of disseminating this kind of knowledge and how stable and objective could it be? The approach of Plato's student Aristotle came to solve this problem. Aristotle characterized episteme as a deductively valid system grounded in necessary truths about natures or essences and he distinguished it from techne, a kind of practical knowledge relating to what we nowadays call technology. Overall, it could

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[14] George Henry, "A Greek-English Lexicon," accessed July 5, 2020, http://www.perseus.tufts.edu/hopper/text?doc=Perseus:text:1999.04.0057:entry=e)pisth/mh.

[15] doxa‹ *ancient greek* δόξα (= a perception or belief) ‹δοκέω/ δοκῶ (believe, think, imagine, guess, assume, decide).

[16] Jessica Moss, "Is Plato's Epistemology About Knowledge?" in *What the Ancients Offer to Contemporary Epistemology*, eds. Stephen Hetherington, and Nicholas D. Smith (Oxfordshire: Routledge, 2019), 1-6.

[17] Ibid., 1-6.

be argued that the purpose of episteme during the Classical era was to explain the world but not to change it. In this context, natural philosophy appeared. The purpose of natural philosophers of the Classical era was not to predict or control the natural world, but to understand, describe, and explain it. In this respect, natural philosophy was different from modern natural science.[18]

Important intellectuals of this era approached the notion of similarity, which acquired increased methodological importance. The roots of the notion of similarity are found in the Pythagorean philosophers, who discerned a relationship between observable phenomena and ratios.[19] They correlated certain musical phenomena with specific length ratios of a lyre string. According to the Pythagoreans, these proportions are equal to the proportions of prime numbers. This observation led them to the conclusion that all physical phenomena could be understood or described in terms of ratios.[20] The analogies found in the study of harmony appeared in other mathematical representations, such as the Tetraktys, a ten-point triangular arrangement consisting of four columns containing one, two, three, and four points, respectively.[21] Moreover, the Pythagoreans traced a relationship among the first four numbers, the sum of which is 10 (1 + 2 + 3 + 4 = 10). From these first four numbers (1, 2, 3, 4), it is possible to construct certain ratios, representing the relationship between two notes, which in music attribute the harmonious musical intervals that Pythagoras first defined in numerical terms.[22] Through a series of experiments, Pythagoras observed that when two strings have the same length, they have the same pitch and the interval between the notes is called a unison.[23] If the length of one string is one-half that of the other string, its pitch is much higher, but they still sound consonant when played together. This interval is represented by the mathematical ratio 2:1 and is called octave [diapason (French) ‹ diapason (Latin) ‹ ή διαπασῶν (Ancient Greek)].[24] If the length of one string is two-thirds that of the other, the strings still sound consonant when played together, and this interval is called a perfect fifth, represented by the ratio 3:2 [perfect fifth ‹ *diapente, sesquialterum* (Latin) ‹ διά πέντε or dioxea ‹ δι οξείαν (Ancient Greek)]. Another

[18] John Reeves, "The Science and Religion Dialogue as Natural Philosophy," *Metanexus*, accessed July 5, 2020, https://www.metanexus.net/science-and-religion-dialogue-natural-philosophy/.

[19] Sterrett, "Similarity and Dimensional Analysis," 799.

[20] Ibid., 799.

[21] Ibid., 799.

[22] Heath, *A History of Greek Mathematics*, 76-86.

[23] Stephanie J. Shaw, *W. E. B. Du Bois and the Souls of Black Folk* (North Carolina: The University of North Carolina Press), 135-136.

[24] Ibid., 136.

Pythagorean interval was 4:3, which is called the perfect fourth [*Diatessaron, sesquitertium* (Latin) ‹ *δια τεσσάρων* (Ancient Greek)].[25]

The Pythagoreans also believed that numbers are related to geometric shapes,[26] owing to the use of sequences of shapes that represent integers, which are created by a specific procedure. In this manner, the unit is related to the point, the dyad to the line, the trinity to the triangle, and the quadruple to the tetrahedron.[27] According to the Pythagorean theory, each integer has a graphical representation. The relationships of analogy between the sides of the shapes that form the sequence are also correlated with specific numbers. Thus, the study of geometrical similarity was initially related to integer relationships.[28] A typical example includes square numbers, such as 4, 9, and 16, the side ratios of which are 2:2, 3:3, and 4:4, respectively, which are all squares, therefore geometrically similar.[29]

The concept of similarity is first detected in geometry in the theorem of the similar triangles by Thales of Miletus, a Greek philosopher and mathematician. According to this theorem:

> Two triangles are equal when they have one side and the angles adjacent to it, equal.[30]

Thales traveled to Egypt and was trained in mathematics by Egyptian priests-mathematicians. Of particular interest is the story in which Thales was able to calculate the height of the pyramids based on their shadow. According to Hieronymus, a disciple of Aristotle, Thales observed the length of the shadow of the pyramids just at the time when the height of our shadow is equal to our real height. The story is presented slightly differently by Plutarch, who in his dialogue between Nikoxenos and Thales presents Nikoxenos to praise Thales for his achievement in calculating the length of the Egyptian pyramids based on the length of their shadow and the shadow of a bar that had entered into the ground.[31] According to this assumption, Thales used the ratio of the sides of two similar triangles and calculated the height of the pyramids from the length of their shadow and the shadow of the bar, thereby impressing the

[25] Ibid., 136.

[26] Sterrett, "Similarity and Dimensional Analysis," 799.

[27] Ibid.,799.

[28] Ibid.,799.

[29] Heath, *A History of Greek Mathematics*, 76-86.

[30] Encyclopaedia Britannica, "Thales of Miletus," accessed November 25, 2019, https://www.britannica.com/biography/Thales-of-Miletus.

[31] Heath, *A History of Greek Mathematics*, 128-130.

Egyptian king Amasi.[32] Thales' work on geometric similarity was completed by the Greek mathematician Euclid. Euclid made an important contribution in terms of defining the concepts of ratio and proportion in his fifth book of *Elements.* According to Euclid:

> A ratio is a sort of relation in respect of size between two magnitudes of the same kind and magnitudes, which have the same ratio are called proportional.[33]

As Douglas Jesseph points out in his article "Ratios, Quotients, and the Language of Nature":

> A ratio is not a quotient formed by the division of one number by another, but rather a relation that holds between geometric magnitudes.[34]

Through his theories, Euclid succeeded in systematizing the existing knowledge, while, at the same time, laying the foundations for what would later be called geometric similarity.[35]

An important contribution to the development of the concept of similarity was that of Aristotle, who understood the concept and used it methodologically. The notion of similarity is found in Aristotle's distinction of the "being" in matter and form, which he defined as the sum of the attributes that each being has in common with other beings and integrates it into a class of similar beings.[36] Aristotle used the "form" in his attempt to describe and categorize animal species in a series of extensive zoological treatises, the most widely known of which is *Περί τα ζώα ιστορίαι* (Animal Histories). In this treatise, Aristotle carefully classified and described 500 species, which he distinguished mainly based on traditional classifications based on multiple features.[37]

We can suggest fairly certainly that during classical antiquity, similarity

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[32] Ibid., 128-130.

[33] Jesseph Douglas, "Ratios, Quotients, and the Language of Nature," in *The Language of Nature*, eds. Geoffrey Gorham, Benjamin Hill, Edward Slowik, and C. Kenneth Waters, 160-177 (Minneapolis: University of Minnesota Press, 2016).

[34] Ibid.

[35] Sterrett, "Similarity and Dimensional Analysis," 799-800.

[36] Lindberg, *Οι Απαρχές της Δυτικής Επιστήμης*, 68-72.

[37] Ibid., 88-90; Αριστοτέλης, *Περί τα ζώα ιστορίαι, Βιβλία Α-Ε,* απόδ. Αλέξανδρος Βασιλειάδης (Θεσσαλονίκη: Εκδόσεις Ζήτρος, 2017); Αριστοτέλης, *Περί τα ζώα ιστορίαι, Βιβλία Κ-Ζ,* απόδ. Αλέξανδρος Βασιλειάδης (Θεσσαλονίκη: Εκδόσεις Ζήτρος, 2018).

played a significant role in the examination, description, and explanation of the world. Ancient Greek philosophers consciously incorporated the mechanism of similarity into their scientific methodology.

IV. The absence of the mechanism of similarity from the research methodology of the Middle Ages (500–1500 AD)

During the Middle Ages, the research focus was mainly on collecting, organizing, and critiquing the existing theoretical knowledge passed down from ancient Greek natural philosophers, in order to serve the purposes of ecumenical church. From 500 AD to 1000 AD, the political and social instability led to the decline of Western science.[38] In order to gain knowledge, the majority of scholars focused mainly on organizing and disseminating ancient Greek science theories and conclusions, but not on the research methodology or experimental techniques used by ancient Greeks.[39] However, during the Late Middle Ages, a number of researchers conducted experiments, but their findings were used to form descriptive encyclopedias rather than to explain or make predictions about natural phenomena.[40] Consequently, until 1200 AD the research activity was not characterized by well-organized and systematic experimentation[41] and the mechanisms, tools, and techniques, such as the mechanism of similarity, of the modern scientific methodology were not being used by the majority of intellectuals.

The appearance of the first universities in the 12th century, contributed to an increase in translations, ancient text critiques, and the organization and expansion of the existing scientific knowledge. After the 13th century, courses on Logic, Physics, Astronomy, Cosmology, and Mathematics were in the core of university education.[42] During this period, the first step of the transition from natural philosophy to science took place within universities. The concept of the scientific hypothesis was introduced into the research process.[43] When researchers were studying ancient texts, they formulated hypotheses in the form of questions, known as "Questions," and they answered them in the form

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[38] Edward Grant, *Οι Φυσικές Επιστήμες τον Μεσαίωνα*, μτφ. Ζήσης Σαρίκας (Ηράκλειο: Πανεπιστημιακές Εκδόσεις Κρήτης, 2013), 1.

[39] Herbert Butterfield, *Η Καταγωγή της Σύγχρονης Επιστήμης (1300-1800)*, μτφ. Ιορδάνης Αρζόγλου και Αντώνης Χριστοδουλίδης (Αθήνα: ΜΙΕΤ, 2010), 79-82; Grant, *Οι Φυσικές Επιστήμες τον Μεσαίωνα*, 7-9.

[40] Butterfield, *Η Καταγωγή της Σύγχρονης Επιστήμης (1300-1800)*, 80-81.

[41] Grant, *Οι Φυσικές Επιστήμες τον Μεσαίωνα*, 8.

[42] Ibid., 32-33.

[43] Ibid., 34-37.

of comments.[44] The introduction of hypotheses in the scientific methodology was an important contribution of the Middle Ages to the development of scientific thought, methodology, and the constitution of new science, of which the research hypothesis is an integral part. After the 14th century, the spread of nominalistic tendencies was gradually observed and the doctrine of "saves the phenomena" was back in the spotlight.[45] These circumstances, along with the strong criticism on Aristotle's natural philosophy, led to the next evolutionary stage of scientific methodology, which appeared during Renaissance.

V. The period of understanding and applying the concept of similarity in the Natural Sciences (16th-19th centuries)

After Copernicus and Galileo's discoveries of celestial bodies and their movements, the preceding scientific methodology was disputed and the ancient explanation of the universe began to collapse[46] and was replaced by new methods and explanatory principles. Eventually, this was followed by the period of the Scientific Revolution (1543-1687), during which the natural sciences advanced rapidly, and the need for a general scientific methodology emerged gradually.[47]

Owing to the Scientific Revolution, the late 17th and 18th centuries saw the appearance of the intellectual movement of the Enlightenment in England and France, respectively; this movement then spread to the rest of Europe. The roots of the Enlightenment are traced in the theory of rationalism, according to which knowledge can be acquired just through pure reason; in other words, the acquisition of knowledge is achieved through a more objective way of thinking that is free from prejudice or from unverifiable assumptions of religious revelation.[48]

The Scientific Revolution and the Enlightenment marked significant changes in the scientific methodology in terms of the perception and explanation of the world, thus laying the foundations for the formulation of the new science. The mechanistic idea,[49] the acceptance of logic as a basic tool of the correct method, and the exploitation of mathematics as the main technique of the experimental method are the three essential characteristics of

44 Ibid., 34-37, 139-140.

45 Ibid., 52-56.

46 Richard S. Westfall, *Η Συγκρότηση της Σύγχρονης Επιστήμης,* μτφ. Κρινιώ Ζήση (Ηράκλειο: Πανεπιστημιακές Εκδόσεις Κρήτης, 2008), 1-34.

47 Butterfield, *Η Καταγωγή της Σύγχρονης Επιστήμης (1300-1800)*, 79-96.

48 Dorinda Outram, *The Enlightenment* (New York: Cambridge University Press, 1995), 1-11, 47-55.

49 Westfall, *Η Συγκρότηση της Σύγχρονης Επιστήμης,* 35-116.

the scientific methodology after the 17th century.[50] These new conditions led to the development of the 17th-century experimental method that sought to turn to nature and directly examine it through systematic experimentation,[51] that is, through the directed and organized observation of the real world through experimental measuring instruments and the development of new scientific techniques utilizing mechanisms and models capable of contributing to the explanation and prediction of phenomena.

In the context of modern science, significant efforts have been exerted to define the concept of similar systems as it was developed after the 17th century and to work out an extensive exploitation of the mechanism of similarity in the natural sciences in the period of modernity (18th-20th centuries).

Galileo used the idea of similar systems in his attempt to explain particular behaviors of machines and structures in general. Galileo focused not only on geometrical similarity, i.e., on the similarity of the dimensions or structures, but also on the proportion of relationships between natural quantities. Galileo made his most important contribution to the development of the concept of similar systems with his pendulum experiments and his law of correspondence. Galileo observed that the quantities determining the behavior of a pendulum are characterized by a constant relationship, which applies to all pendulums. These quantities are the oscillation time and the length of the pendulum's string. According to his observations, the ratio of the length of the string to the frequency of the pendulum oscillations is constant and applies to every pendulum. This constant ratio constitutes a correspondence law, which correlates each of these two quantities of one pendulum with their corresponding quantities in another pendulum, thereby allowing Galileo to calculate the length of a pendulum's string from the number of oscillations of the two pendulums at a given time. The idea that each pendulum relates to another pendulum with a law of correspondence, forms the basis of the idea of similar systems.[52]

During the early 17th century, the application of the mechanism of similarity can be traced in experimental physics and, more specifically, in the study of "subtle" or "imponderable" fluids. The movement of electricity, heat, gravity, and magnetism, which have physical properties, but do not

[50] Butterfield, *Η Καταγωγή της Σύγχρονης Επιστήμης (1300-1800)*, 79-96; Thomas L. Hankins, *Επιστήμη και Διαφωτισμός*, μτφ. Γιώργος Γκουνταρούλης (Ηράκλειο: Πανεπιστημιακές Εκδόσεις Κρήτης, 1998), 1-10, 12, 25-32; Outram, *The Enlightenment*, 47-55.

[51] Butterfield, *Η Καταγωγή της Σύγχρονης Επιστήμης (1300-1800),* 79-96; Hankins, *Επιστήμη και Διαφωτισμός*, 67-73; Westfall, *Η Συγκρότηση της Σύγχρονης Επιστήμης*, 35-36, 162-169.

[52] Sterrett, "Physical Models and Fundamental Laws," 57-59; Sterrett, "Physically Similar Systems," 384-387.

constitute regular material,[53] conveys their physical properties, but it does not carry mass. When researchers observed heat flowing from a hot to a cold object, they did not detect any changes in mass.[54] In order to describe and explain this movement, they compared its similarity to the motion of fluids. Until then, the concept of similar systems may not had been defined, but knowledge on subtle fluids allows us to infer that scientists had understood the role of similarity in the process of drawing scientific conclusions and had incorporated it into their scientific methodology when they considered that it would be useful.

In late 17th century, Newton in his second book of Principia, defined the concept of similar systems for first time in the history of the concept, as follows:

> Suppose two similar systems of bodies consisting of an equal number of particles, and let the correspondent particles be similar and proportional, each in one system to each in the other, and have a like situation among themselves, and the same given ratio of density to each other; and let them begin to move among themselves in proportional times, and with like motions (that is, those in one system among one another, and those in the other among one another). And if the particles that are in the same system do not touch one another, except in the moments of reflection, nor attract, nor repel each other, except with accelerative forces that are inversely as the diameters of the correspondent particles, and directly as the squares of the velocities: I say, that the particles of those systems will continue to move among themselves with like motions and in proportional times.[55]

In order to assess if two systems were similar, Newton focused on geometrical and structural (mass, density) similarities between two systems of bodies, the proportion of the movement between particles, and the movement duration.[56] In contrast to Galileo, who used the idea of similar systems as a specialized method aimed at explaining exclusively the behavior of pendulums, Newton presents the idea of similar systems as a method with general applications.[57]

[53] Hankins, *Επιστήμη και Διαφωτισμός*, 73-78.

[54] Ibid., 73-78.

[55] Sterrett, "Physically Similar Systems: A History of the Concept," 382.

[56] Ibid., 382-383.

[57] Ibid., 382-387.

Newton's approach was the starting point for the examination of the concept of similar systems, sparking a series of theories from researchers coming mainly from the fields of natural sciences and engineering. The term "similar systems" introduced by Newton was a reference point until the early 20th century.

It is clear that this period was characterized by extensive efforts to understand and define similarity. This proves that the Scientific Revolution and the Enlightenment contributed significantly to the development of the concept of similarity and to the utilization of the mechanism of similarity as an experimental technique of the natural sciences after the 17th century. However, it is worth noting that despite the significant changes in the scientific methodology developed during this period, the terms "science" and "scientist" did not appear until the 1830s, when they were first used in England; until then, the term natural philosophy was used instead.[58]

VI. The stage of the systematic utilization of the mechanism of similarity in the natural sciences (19th–21st centuries)

An important year for the development of the concept of similar systems was 1914, as it was then that Edgar Buckingham, an American physicist, proposed the term "physically similar systems" in order to replace Newton's previously accepted term "similar systems." His approach was as follows:

> Let S be a physical system, and let a relation subsist among a number of quantities Q, which pertain to S. Let us imagine S to be transformed into another system S' so that S' "corresponds" to S as regards the essential quantities. There is no point of the transformation at which we can suppose that the quantities cease to be dependent on one another: hence we must suppose that some relation will subsist among the quantities Q' in S', which correspond to the quantities Q in S. If this relation in S' is of the same form as the relation in S and is describable by the same equation, the two systems are "physically similar" as regards this relation.[59]

A common characteristic between Newton's and Buckingham's approaches of the concept of similar systems was the identification of a ratio between physical quantities or the relationship of physical quantities. While Newton defined similar systems on the basis of their similar structural characteristics

[58] Outram, *The Enlightenment,* 48-49.

[59] Sterrett, "Physically Similar Systems: A History of the Concept," 380-381.

(mass and density), Buckingham defined them on the basis of the proportional relationships observed between specific physical quantities of interest. Since 1914 the term “physically similar systems” introduced by Buckingham, has been widely accepted and used up to this day.

The systematic utilization of similarity extended significantly after the 19th century, mainly in the fields of Engineering and Physics. William Froude developed an interesting approach focusing on utilizing the similarity mechanism for ship design and construction. William Froude was an English engineer who got involved in hydrodynamics and ship design during the early 19th century. He utilized the concept of similar systems to solve major problems encountered in the construction of ships for the English Navy; these problems had to do with stability, ship speed, and the interaction between ships and water in motion or stillness.[60] The notion of similar systems in Froude, as in Newton, took into account correlating quantities in one situation with corresponding quantities in another situation.[61] In particular, Froude carried out experiments with ship scale models and extended the inferences of his experiments, through the appropriate calculations, to full-sized ships.[62]

VII. Similarity as a core mechanism of scientific models in modern science: Susan G. Sterrett’s view

Susan G. Sterrett is a Professor of History and Philosophy of Science at Wichita State University in Kansas, US. While she initially studied Mechanics, later on her research interests focused on the field of History and Philosophy of Science. Her work focuses on issues related to the methodology of science, with her major contribution being highlighting the importance of similarity concepts and scientific models in the field of Philosophy of Science; the significance of such concepts has already been recognized in natural sciences and engineering.

According to Sterrett, the concept of similarity is powerful in the field of natural sciences and should be further examined and developed in other fields. Sterrett accepts the idea that the concept of similarity is related to the concept of ratio. She understands the concept of physical similarity as a generalization of the concept of geometrical similarity. While geometrical similarity is defined by the ratio of shapes or distance between two points, physical similarity is defined by the proportion of physical quantities pertaining to similar systems, such as time, mass, and force. In order to generalize the notion of similarity so as to apply it not only to geometry

[60] Ibid., 389-393.

[61] Ibid., 389-393.

[62] Ibid., 389-393.

but to natural sciences as well, the concepts of proportion and shape also had to be generalized.[63] Sterrett's significant contribution to the evolution of the concept of similarity is in highlighting the importance and the role of the scientific hypothesis in the light of which the similarity between two physical systems is determined. According to her, two systems can be characterized as physically similar when there is an analogy between specific relationships of corresponding physical quantities, which is always defined in the light of a scientific hypothesis.[64] This important observation by Sterrett contributes to a clearer definition of the concepts of similarity and similar systems, thereby placing her theory among the most important evolutionary stages of these concepts.

Another important issue that concerned Sterrett was in what types of methodology is the similarity mechanism used and how are the criteria that determine the similarity between two bodies or systems selected.[65] She points out that since the beginning of the 19th century the mechanism of similarity has been associated with the concept of the scientific model, a core experimental technique widely utilized, especially in natural sciences. The importance of scientific models in describing, explaining, and predicting the natural world is recognized by researchers that are active in many scientific fields globally. Sterrett has examined extensively the utilization of the mechanism of similarity as the basic operating mechanism of scientific models.

The majority of scientists working in the field of philosophy of science perceive scientific models as theoretical tools, which constitute an intermediate stage between theory and the real world.[66] These tools are formed by theory, laws, and principles that relate to the subject under consideration and they are used to draw conclusions about real-world situations.[67] Sterrett considers this approach as fragmentary, as it does not include a wide range of models, which are not theoretical tools of an intermediate stage, but parts of the real world, such as scale models in physics and mechanics or animal models in biology. She proposes the classification of scientific models in the categories of "realm of thought" and "using one piece of the world to tell about another." The first category includes models of abstract and mathematical structures as well as algorithms or mechanism descriptions. These tools are considered

[63] Sterrett, "Similarity and Dimensional Analysis," 800-801.

[64] Sterrett, "Models of Machines and Models of Phenomena," 69-80.

[65] Ibid., 69–80.

[66] Susan G. Sterrett, "Kinds of Models," in *The Multiple Meanings of Models* (John Hope Franklin Center: Duke University, 2003), 1-2, http://philsci-archive.pitt.edu/2363/.

[67] Sterrett, "Physical Models and Fundamental Laws," 56-59; Sterrett, "Kinds of Models," 1-2.

models in virtue of their relationship to some equations or formal scientific proposals.[68] Models that fall into the second category are parts of the real world. These models are commonly known as analogue models.[69] Analogue models are physical set-ups that are utilized as models of other physical set-ups, which researchers cannot observe because of their size as well as the space or time that separates them from them. The basic function of their mechanism is similarity, which is validated by a ratio of physical quantities or by a ratio of relationships observed between the physical quantities of two phenomena or objects. The analogue relationships between the model and the system of interest are based on the direction and purpose of the research, which are determined by the scientific hypothesis.[70] Similarity is defined by criteria that are determined by the phenomenon of interest and the problem to be solved. Therefore, the similarity between the model and the object of interest is usually not absolute, as it is defined in respect to a particular characteristic, which, in turn, is defined through the formulation of the scientific hypothesis.

Examples of analogue models are scale models that are extensively used in engineering and physics. Scale models are physical objects or systems, which are used to control or predict the behavior of a machine, an object, or a system of different dimensions. They are constructed in such a way that they are proportionate to an object in the physical world.[71]

Sterrett described the operation stages of scale models in order to present the utilization of the similarity mechanism in the context of this scientific technique. According to Sterrett, in the first stage, the researcher should study the physical quantities related to the phenomenon of interest. Then they should construct a physical state S2, which is similar to state S1, in the areas of their research interest. In other words, the researcher chooses the proportional relationship, which could correspond to their scientific hypothesis and constructs the model based on this relationship. This way, the researcher can define similarity based on their specific research hypotheses. Then, they develop the rules for transferring prices of quantities of S2 to S1 (principles, laws, and equations). Once the S2 model is constructed, the

[68] Sterrett, "Kinds of Models," 1-2, 9-11.

[69] Susan G. Sterrett, "Experimentation on Analogue Models," in *Springer Handbook of Model-Based Science*, eds. Lorenzo Magnani, and Bertolotti Tommaso (Cham: Springer International Publishing, 2017), 357-360.

[70] Sterrett, "Physical Models and Fundamental Laws," 59-63; Sterrett, "Models of Machines and Models of Phenomena," 69-80.

[71] Sterrett, "Kinds of Models," 1-3; Sterrett, "Physical Models and Fundamental Laws," 59-63; Sterrett, "Models of Machines and Models of Phenomena," 69-80; Sterrett, "Experimentation on Analogue Models," 360-362.

researcher measures the quantities, observes the behavior of the physical state, and draws inferences about the S1 state.[72]

We strongly believe that Sterrett's contribution is highly important because she opened a constructive dialogue in the field of philosophy of science on concepts, such as similar systems and scientific models that have been sufficiently examined, defined, and widely used in the experimental method of the natural sciences. Sterrett identified that the concept of similarity has been neglected in modern philosophical thought, thus managing to highlight the necessity for its further examination. Through her research, she laid the foundation for further investigation, with the main aim being to overcome problems, such as the inadequate understanding of similarity, similar systems, and scientific model concepts that sometimes lead to their fragmentary perception and their non-acceptance as formal scientific techniques by philosophers of science.

Working in this direction, Sterrett managed to contribute significantly to the sufficient definition and evolution of these concepts, with her main contributions being that she highlighted the importance and the role of the scientific hypothesis, in the light of which the similarity between two physical systems is determined, but also her observation, according to which the mechanism of similarity is the basic operating mechanism of scientific models. In this context, the mechanism of similarity could be understood as a set of rules, laws, principles, or mathematical relationships utilized by the analogue modeling technique in order to successfully validate a certain analogue relationship between the model and the system of interest in the context of a scientific hypothesis. This mechanism is utilized not only when the model is selected or constructed, but also during the process of extending the model's inferences to the object, system, or phenomenon of interest, always in light of the scientific hypothesis in question.

In this context, it becomes clear that Sterrett's contribution is not limited to her argumentation or her theories on the similarity, similar system, and scientific model concepts, which was undoubtedly important too. It could be argued that her most important contribution was highlighting how neglected these concepts are in the field of philosophy of science and how important is their further investigation. If the detection of existing knowledge during a research process is considered important, then the detection of absent knowledge should be accepted as a powerful motive able to motivate new research steps, reveal new research directions, and contribute to the development and evolution of science. We support that through the philosophical perspective, these concepts could be documented in a theoretical manner more sufficiently and recognized as formal techniques

[72] Sterrett, "Physical Models and Fundamental Laws," 56-58.

not only of the modern scientific methodology of natural sciences, but also in modern science overall.

VIII. Conclusions

The present historical review of the concept of similarity presented the evolution of conceptualizing and utilizing the mechanism of similarity as a practical and experimental technique, applicable to the scientific methodology of the natural sciences in various eras of human intellectual activity. The historical evolution of similarity was examined in the context of different historical periods, ranging from antiquity to the present day and is directly related to the evolution of scientific thought. According to this approach, the concept of similarity went through five distinct stages of evolution. The first stage corresponds to Egyptian science from 3200 BC to 1200 BC and it could be characterized as the beginning of the utilization of similarity, which enabled ancient Egyptians to achieve various architectural, medicinal, and mathematical feats. During this period, ancient Egyptians used similarity in a generalized manner, as a technique to categorize knowledge and contribute to the description, explanation, and prediction of the world, primarily aimed at solving practical problems. However, it is not clear to what extent the concept of similarity was defined in Egyptian science. The second stage corresponds to the Classical era, which is the era of the genesis of episteme and natural philosophy, when the notion of similarity appeared in philosophy, mathematics, music, and geometry and was perceived to be of increased methodological importance. During the Classical era, similarity was perceived and exploited consciously for the first time, while it was developed in the context of a more general attempt to describe and explain the world as viewed by ancient Greek philosophers.

The third stage was during the Dark Ages, a time of scientific stagnation. The medieval period proved unfavorable for the exploitation and development of experimental scientific techniques and mechanisms, such as the mechanism of similarity. It follows that during the Dark Ages, similarity was absent from scientific methodology. During the next evolutionary stage, after Renaissance, the concept of similarity gained renewed importance, this time as the methodological idea of similar systems. In particular, this was the period of defining and consciously utilizing similarity as an experimental tool of the natural sciences (late 16th century to early 19th century). Finally, the fifth stage corresponds to the period from the 19th century to the 21st century and constitutes the stage of the theoretical documentation and systematic application of the mechanism of similarity in the natural sciences as well as the extension of its application in many scientific fields. Two dominant theories on the concept of similarity originated in this period. The first is that of Edgar Buckingham who introduced the term "physically similar systems," which is used up to the present day. The second is that of modern philosopher of science Susan G. Sterrett who highlighted the necessity to research further the concepts of similarity, similar systems, and scientific models in the field of Philosophy of Science, concepts whose significance had already been recognized in the natural sciences and engineering.

The study of the historical evolution of similarity clarifies that the transition from the "technocratic" exploitation of similarity to its theoretical documentation as well as to its conscious and systematic application as a tool of scientific methodology was not completed in a single evolutionary stage. On the contrary, it took many centuries for the concept to evolve in parallel with the evolution of scientific thought and to reach its modern significance and application within the scientific methodology of the natural sciences. The transition from the "technocratic" utilization of similarity to its conscious utilization can be detected in the classical era stage. The transition to its systematic use as a significant experimental tool is traced after Renaissance. Finally, the theoretical documentation of the concept of similarity and efforts to expand its application to more scientific fields, are traced after the 19th century. Although all stages contributed to the development of the concept of similarity, the period after the scientific revolution is considered crucial for the conceptualization and utilization of the mechanism of similarity. The changes that occurred in science after the Scientific Revolution and the Enlightenment played a decisive role in the evolution of the concept of similarity. The Scientific Revolution and the Enlightenment helped shape a new way of thinking that changed the way scientists research the natural world. The incorporation of systematic experimentation into scientific methodology resulted in the need to develop new scientific practices, including measuring instruments and the systematic exploitation of mechanisms and scientific models capable of contributing to the explanation and prediction of phenomena. These conditions contributed to the immediate adoption of the mechanism of similarity and to its systematic application in scientific models, which was greatly expanded from the 18th century onwards. Moreover, from Newton's concept of geometrical similarity to Buckingham's concept of physical similarity, and finally to the concept of physical similarity in the light of a specific research hypothesis in Sterrett's approach, these circumstances enabled the adoption of a multifaceted approach, a deeper understanding, and a more sufficient definition of the concept of similarity and its evolution.

Sterrett's significant addition contributes to a clearer definition of the concepts of similarity and similar systems. The emphasis she placed on the significance of the scientific hypothesis during the process of defining the similarity between two systems, rightly places her theory between the important evolutionary milestones of concepts of similarity and similar systems. Except for this, Sterrett observed that the concepts of similarity, similar systems, and scientific models are neglected in modern philosophical thought and recognized the necessity to further examine them in the field of the philosophy of science. This view seems reasonable, as a more systematized philosophical research of these concepts could lead to a more comprehensive understanding, better clarification, description, and adequate theoretical documentation of them. A meticulous philosophical study of these concepts could reinforce the existing theory coming from natural science research and contribute to their safer and more efficient use as methodological tools and the expansion of their application into other scientific areas. Thus, Sterrett pointed out the absence of sufficient theories and knowledge regarding the concept of similarity in the field of philosophy of science, thereby provoking an open and constructive dialogue in this field.

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