Ancient Greek *Mathēmata* from a Sociological Perspective: A Quantitative Analysis

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Abstract: This essay examines the quantitative aspects of Greco-Roman science, represented by a group of established disciplines that since the fourth century B.C.E. had been called *mathēmata* or *mathēmatikai epistēmai*. Among the *mathēmata*, which in antiquity normally comprised mathematics, mathematical astronomy, harmonics, mechanics, and optics, the essay also includes geography. Using a data set based on *The Encyclopaedia of Ancient Natural Scientists*, it considers a community of *mathēmatikoi* (as they called themselves), or ancient scientists (as they are defined for the purposes of this essay), from a sociological point of view, focusing on the size of the scientific population known to us and its disciplinary, temporal, and geographical distribution. A diachronic comparison of neighboring and partly overlapping communities—ancient scientists and philosophers—allows the pattern of their interrelationship to be traced. An examination of centers of science throughout ancient history reveals that there were five major sites—Athens, Alexandria, Rhodes, Rome, and Byzantium/Constantinople—that appeared, in succession, as leaders. These conclusions serve to reopen the issue of the place of *mathēmata* and *mathēmatikoi* in ancient society.

The historiography of ancient Greek science is nearly as old as its subject. The earliest known writings on the history of mathematics and astronomy belong to Eudemus of Rhodes, a pupil of Aristotle. When, after a long period of decline and oblivion in medieval Europe, the sciences were revived, it was ancient Greek science that became the primary subject of Renaissance and early modern studies in the history of science. From the eighteenth century onward, ancient science was studied from what then seemed a self-evident cognitivist

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The references to Latin and Greek sources are abbreviated according to *The Oxford Classical Dictionary*, 4th ed.; the list of abbreviations is available online at http://classics.oxfordre.com/staticfiles/images/ORECLA/OCD.ABBREVIATIONS.pdf.

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perspective, with a particular focus on its methods, techniques, theories, and discoveries. In the 1930s through the 1950s, the dominant position of the internal history of ancient science was challenged by a group of Marxist-oriented historians of science, who attempted to apply social (in this particular case, class) analysis to the *content* of Greek mathematics and astronomy—looking, for example, for the direct influence of the social status of a scientist on his theories.[1] After this kind of analysis proved to be unsuccessful, the sociological dimension of Greek science receded far into the background. The postwar sociology of science has been developed on the basis of early modern and more recent materials.

Two main factors explain the situation. First, a shortage or total absence of basic empirical evidence on ancient scientists hampers the quantitative analysis and generalization practiced in sociology of science. In order to comprehend the situation, we need to imagine knowing as little about Kepler and Galileo as is known about Euclid and Apollonius of Perga: only their names, native cities, and approximate dates—and even those dates are disputed. The second factor, obviously connected to the first, is that ancient science is held to have been so poorly developed institutionally that it has been, and continues to be, regarded as the product of individuals dispersed in space and time—and thus as hardly suitable for sociological inquiry. Early modern science is often seen as a radical departure from ancient science both in its cognitive foundations and in terms of its embeddedness in social practice, its relationship with technology and the state, the number and social standing of scientists and their role in society, and so forth. The shared *social* characteristics and tendencies of ancient and early modern science are usually not given close consideration by sociologists of science.

A conspicuous example of this neglect is the chapter "Sociology of Greek Science" in the classic book by Joseph Ben-David, *The Scientist's Role in Society*. Ben-David suggested that it was not until the seventeenth century that certain people first viewed themselves as scientists and that the scientific role, with its "unique and special obligations and possibilities," emerged and became institutionalized—"i.e. recognized as a legitimate, indeed prestigious, social activity."[2] As is evident from Ben-David's book—and this is even clearer in the early essay out of which this work developed—he did not study ancient science himself but relied entirely on the work of a few experts on the topic, first and foremost Ludwig Edelstein. In Edelstein's depiction, Greek science never became markedly differentiated from philosophy and religion, since the motives for engaging in it were religious and aesthetic and its methodology rested on philosophical grounds. Ben-David's verdict was that "ancient science failed to develop not because of its immanent shortcomings, but because those who did scientific work did not see themselves as scientists. Instead they regarded themselves primarily as philosophers, medical practitioners, or astrologers."[3]

There is no doubt that had Ben-David chosen other authorities or applied his own sociological concepts—scientific role, reference group, institutionalized norms and rewards, and so forth—to the ancient sources, his picture of Greek science would have been quite different; and that, in turn, might have encouraged other sociologists to investigate it in more detail. But

[1] For eighteenth-century works in the history of science see, e.g., Jean Étienne Montucla, *Histoire des mathématiques*, 2 vols. (Paris: A. Jombert, 1758). For the Marxist approach see Salomo Luria, "Die Infinitesimaltheorie der antiken Atomisten," *Quellen und Studien zur Geschichte der Mathematik*, 1932, 2:106–185; Dirk Struik, "On the Sociology of Mathematics," *Science and Society*, 1942, 6:58–70; and John Bernal, *Science in History*, Vol. 1: *The Emergence of Science* (London: Watts, 1954).

[2] Joseph Ben-David, *The Scientist's Role in Society* (Englewood Cliffs, N.J.: Prentice-Hall, 1971), pp. 33–45, on p. 45; and Gad Freudenthal, "Introduction to Joseph Ben-David's 'Scientific Growth: A Sociological View,'" in Ben-David, *Scientific Growth: Essays on the Social Organization and Ethos of Science*, ed. Freudenthal (Berkeley: Univ. California Press, 1995), pp. 295–297, on p. 295.

[3] Ben-David, *Scientist's Role in Society*, p. 45. For the early version of Ben-David's work on this topic see Joseph Ben-David, "Scientific Growth: A Sociological View," *Minerva*, 1964, 3:455–476. For Edelstein's views see Ludwig Edelstein, "Motives and Incentives for Science in Antiquity," in *Scientific Change*, ed. Alistair C. Crombie (London: Heinemann, 1963), pp. 15–41.

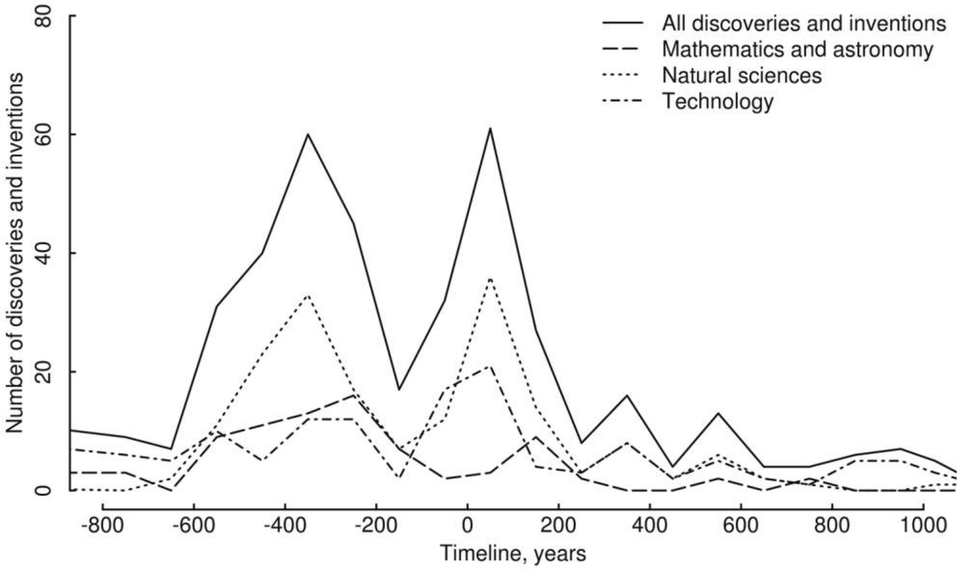

Figure 1. Scientific discoveries and technological inventions (800 B.C.E.–1000 C.E.), according to Ptirim Sorokin and Robert Merton.

since his work in fact served to close rather than open up the field, our attempt to examine a community of ancient scientists as a whole in its quantitative aspects—which can compensate at least in part for the lack of empirical data on individual scientists—has to start from the most general questions. Who were the people referred to as "ancient scientists" in this essay and how did they view and describe themselves? What is the approximate number of those known to us and what disciplines were they engaged in? Can we identify some meaningful patterns in the temporal and spatial distribution of ancient scientists, which would help us to understand the evolution of ancient science and its individual disciplines? To what extent did scientific activity overlap with philosophical engagement? What centers of science existed throughout ancient history and how did they succeed each other? The answers to these questions will help us to define the place of *mathēmata* and *mathēmatikoi* in ancient society more precisely.

I. SOME HISTORIOGRAPHY

In view of the notable lack of special studies in the sociology of ancient science, it seems important to present a short overview of a few works that attempted quantitative analysis of the evidence. Priority here belongs to one of the founders of empirical sociology, Pitirim Sorokin, whose *Social and Cultural Dynamics* paid attention to the development of science and technology from the earliest times. On the basis of Ludwig Darmstädter's classic overview of scientific and technological discoveries, Sorokin and his student Robert Merton counted discoveries in various fields of science and technology in different cultures.[4] Their graph of the development of ancient science and technology (see Figure 1, solid line) takes into account the exact and natural sciences, geographical discoveries, and technical inventions. It shows two peaks of activity, located at 375 B.C.E. and 70 C.E., with a deep recession between them, around 125–

[4] Ludwig Darmstädter, *Handbuch zur Geschichte der Naturwissenschaften und der Technik* (Berlin: Springer, 1908); and Pitirim Sorokin, *Social and Cultural Dynamics*, Vol. 2 (New York: American Book, 1937), p. 137. See also Sorokin and Robert K. Merton, "The Course of Arabian Intellectual Development, 700–1300 A.D.: A Study in Method," *Isis*, 1935, 22:516–524.

175 B.C.E. Of special interest for us is the graph of the discoveries in mathematics and astronomy (dashed line), which shows two smaller peaks at 250 B.C.E. and 150 C.E. We shall return to this picture later in the essay (see Section V, after note 53).

In Alfred Kroeber's famous *Configurations of Culture Growth*, which considered the ability to create outstanding work in the arts and sciences a measure of the prosperity of a society, a short chapter is devoted to ancient Greek science (other chapters treat philosophy and medicine). Kroeber took as his unit of measurement of scientific creativity not discoveries but geniuses or talents—that is, outstanding and eminent scientists. He identified 83 figures, ranked them in order of importance, and used his findings to construct a diagram of the development of ancient science. Kroeber estimated its total duration at nine centuries—from Thales to Diophantus and Pappus—and regarded three of these centuries as unproductive in terms of new ideas and methods. He identified the culminating phase of ancient science as 310–120 B.C.E. (the climax in 310–200 B.C.E. and its continuation in 200–120 B.C.E., for 190 years in total); this was followed by a period of "qualitative quiescence and quantitative growth" (120 B.C.E.– 120 C.E.) and then by two brief peaks (120–170 C.E. and 250–300 C.E.) and definitive decline. Thus, independently of Sorokin and using different methods, Kroeber came to similar conclusions.[5]

Since Kroeber's time the concept of decline as applied to antiquity has fallen out of fashion; many historians regard "decline" as an outdated historiographical notion and avoid the term.[6] Nevertheless, the concept of decline, properly defined, has not lost its analytical power, as H. Floris Cohen's wide comparative study of the history of science in several civilizations demonstrates. Without using Kroeber's model or any quantitative methods, Cohen arrives at a view very close to that of Kroeber: "in each case an upswing takes place that within two to three centuries culminates in a relatively short-lived 'Golden Age,' and then a steep downturn occurs that is nevertheless punctuated by some rare, individual achievements at a level of quality far above what has in the meantime become standard."[7]

The next attempt to apply quantitative methods to Greek science and analyze the results in some detail was made fifty years later by a renowned expert in Greek mathematics, Reviel Netz. He too started his analysis from the very beginning—specifically, by seeking to determine the number of Greek mathematicians and their chronological and geographical distribution. As a selection criterion Netz suggested the following definition: "Whoever has written (or perhaps merely produced orally) an argument showing the validity of some claim, using the techniques we identify with Greek mathematics . . . is, in my opinion, a mathematician." Those who did not produce proofs (astronomical observers, calculators, astrologers) are not included in the list of 144 mathematicians Netz compiled. All the Greek mathematicians he identified were distributed between two principal centers—Athens and then Alexandria—with several "peripheral scatters" around them.[8] Their chronological distribution (see Figure 2) indicates that the number of mathematicians only once, around 340 B.C.E., exceeded 15 persons; the number usually fluctuated between 5 and 10. Note the deep recession that runs from 210 B.C.E. until 50 C.E., when the number of mathematicians dropped to zero. Relying on these data, Netz presented a

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[5] Alfred L. Kroeber, *Configurations of Culture Growth* (Berkeley: Univ. California Press, 1944), pp. 100–114, 205–206 (quotation). For comparison of the two methodologies see Dean K. Simonton, "Kroeber's Cultural Configurations, Sorokin's Culture Mentalities, and Generational Time-Series Analysis," *Comparative Civilizations Review*, 2003, *49*:96–108.

[6] "It seems very hard for many people working on Late Antiquity to consider the possibility that anything was declining. Instead they prefer to see change and transformation." Adrian Goldsworthy, *The Fall of the West* (London: Weidenfeld & Nicolson, 2009), p. 5.

[7] H. Floris Cohen, *How Modern Science Came into the World: Four Civilizations, One Seventeenth-Century Breakthrough* (Amsterdam: Amsterdam Univ. Press, 2010), pp. 27–33, on p. 28.

[8] Reviel Netz, "Classical Mathematics in the Classical Mediterranean," *Mediterranean Historical Review*, 1997, *12*:1–24, on pp. 4 (definition), 2–3 (distribution).

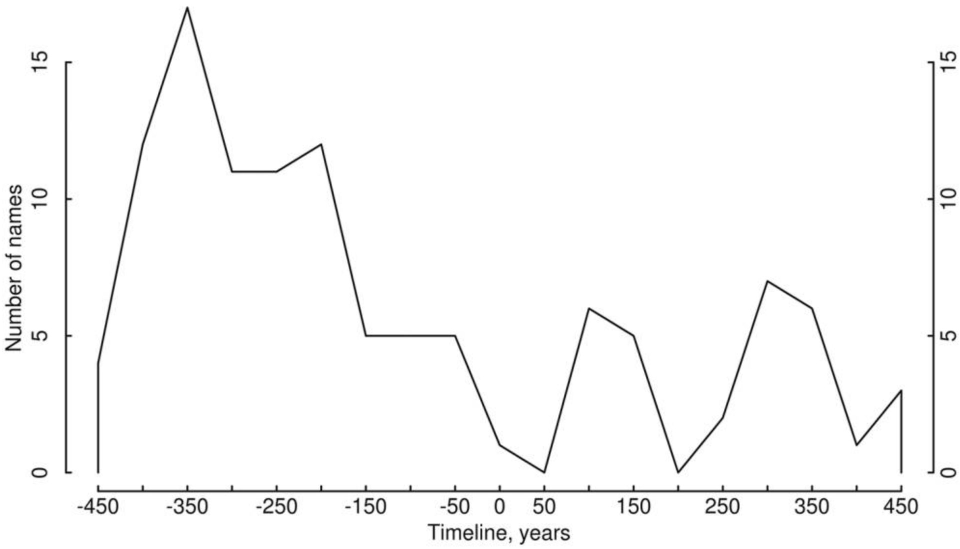

Figure 2. Greek mathematicians, according to Reviel Netz.

"group picture" of Greek mathematicians, analyzing their gender, age, ethnicity, social standing, mobility, and so forth and offering very interesting considerations on the place of mathematics in ancient society.[9]

The last item in our overview is a recent statistical survey of the philosophical "population" of antiquity by Richard Goulet that offers rich comparative material. It is based on the well-known *Dictionnaire des philosophes antiques*, which Goulet has edited since 1989. From the 2,997 names in the general listing of the *Dictionnaire*, Goulet has chosen 2,463 historical figures, dating from the sixth century B.C.E. to the sixth century C.E., who fit his chief criterion for a philosopher: "to have been described as a philosopher or a philosopher of some philosophical school in ancient sources, to have produced or have been said to have produced philosophical treatises, to have expressed unmistakably philosophical ideas, or to have taught philosophy to some disciple(s)."[10] Those physicians, scientists of various kinds, astrologers, alchemists, magicians, statesmen, generals, monks, and bishops who are called "philosophers" in ancient sources but who do not meet Goulet's descriptive criterion are excluded from his database.[11]

II. DEMARCATING ANCIENT SCIENCE

Our inquiry is based on the *Encyclopedia of Ancient Natural Scientists* (*EANS*), which offers the most complete state-of-the-art database on ancient scientists.[12] *EANS* provides 2,043 entries

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[9] Reviel Netz, "Greek Mathematicians: A Group Picture," in *Science and Mathematics in Ancient Greek Culture*, ed. Christopher J. Tuplin and Tracey E. Rihll (Oxford: Oxford Univ. Press, 2002), pp. 196–216. Cf. Section VII, text preceding note 77.

[10] Richard Goulet, "Ancient Philosophers: A First Statistical Survey," in *Philosophy as a Way of Life: Ancients and Moderns: Essays in Honor of Pierre Hadot*, ed. M. Chase, Stephen R. L. Clark, and M. McGhee (Chichester: Wiley-Blackwell, 2013), pp. 10–39, on pp. 12–13. For the dictionary see Goulet, ed., *Dictionnaire des philosophes antiques*, 7 vols. (Paris: CNRS Editions, 1989–2018).

[11] Goulet's database can be easily reduced by two hundred names if we consider that a list of the 228 Pythagoreans in Iamblichus (*Vit. Pyt.* 267) mostly contains members of the Pythagorean *hetaireiai*, not philosophers. See Leonid Zhmud, *Pythagoras and the Early Pythagoreans* (Oxford: Oxford Univ. Press, 2012), pp. 105–118. It is no wonder, then, that in Goulet's graphs the Pythagorean school always skews his results.

[12] Paul T. Keyser and Georgia L. Irby-Massie, eds., *The Encyclopedia of Ancient Natural Scientists: The Greek Tradition and Its Many Heirs* (London: Routledge, 2008). The international team of *EANS* authors includes more than 120 specialists.

(276 of them are new, figures or texts not mentioned in earlier scholarly literature), a geographical gazetteer of all ancient cities and places mentioned in the text with their coordinates, a detailed chronological table, and indexes of persons organized by discipline and field of knowledge. The downside of this completeness is its editors' very broad, almost all-inclusive view of science.[13] In accordance with such a view, *EANS* includes figures whose interests spanned quite diverse topics and types of activities, which can be roughly divided into four groups: fields of knowledge that achieved scientific status in antiquity, such as geometry, arithmetic, mathematical astronomy, optics, and the like; disciplines that crossed the threshold from prescientific thought only in modern times, in some cases as late as the nineteenth century: physics, zoology, meteorology, psychology, and so forth; activities that, not being sciences in themselves, were grounded from the mid-nineteenth century onward on a solid scientific basis: medicine, pharmacology, agriculture, and the like; and fields of knowledge that have never been and are not now sciences: alchemy, astrology, physiognomics, paradoxography. In sum, ancient physicians (420), "pharmacologists" (500), alchemists (56), astrologers (96), and paradoxographers (61) constitute more than half of the *EANS* entries. This approach differs markedly both from that of Netz, who did not include astrologers, calculators, or philosophical lovers of mathematics (Plato, Iamblichus, etc.) in his list, and from that of Goulet, who excluded scientists, physicians, astrologers, and alchemists from his corps of philosophers.

Roughly speaking, attitudes to ancient science can be reduced to two generalities: that it was very similar to modern science or very different from it. Both positions have their merits but also their drawbacks. Thus, the first allows some scholars unproblematically to ascribe the epistemological status of contemporary scientific disciplines, such as biology or psychology, to their ancient predecessors, which did not possess it. Meanwhile, the history of science can point to a number of disciplines—for example, physics—that, having existed for many centuries in the framework of natural philosophy, acquired scientific status over time, while others—for example, physiognomics—never succeeded in achieving it. It is perfectly legitimate to study ancient meteorology from the perspective of the history of science as long as we do not forget that it was a part of natural philosophy.[14] A quest for *prōtoi heuretai*, authors of important discoveries and inventions that, over the course of time, became an integral part of science, is inherent to the historiography of science.[15] But we should not take individual discoveries, however brilliant, to be the beginning of a *stable scientific discipline*; that happens only when a discipline acquires methods of efficiently generating indisputable knowledge shared by the whole scientific community (e.g., deductive proof in mathematics, systematic experimentation in physics). Thus Aristotle and Theophrastus, exploring a wide range of natural problems, laid the first foundations of zoology and botany, but these studies were not further developed in antiquity and became classic examples of abortive sciences.[16] The early Hellenistic doctor Erasistratus was the first to study human anatomy systematically; he discovered motor nerves, elaborated a quantitative theory of pulse, and so on. But, again, human anatomy did not become a distinctive research field in antiquity.

The second attitude sees things very differently. Thus, for example: "Ancient scientists were not working to our notion of scientific method—which is why some scholars contend that the

[13] "Science, with technology, exists in some form in every culture, and consists at a minimum of collections of recipes held to be efficacious; typically, we find that the collections of recipes are organized and systematic, and come with principles conceived to explain them." Paul T. Keyser, "The Name and Nature of Science: Authorship in Social and Evolutionary Context," in *Writing Science: Medical and Mathematical Authorship in Ancient Greece*, ed. Markus Asper (Berlin: De Gruyter, 2013), pp. 17–61, on p. 17.

[14] Liba Taub, *Ancient Meteorology* (London: Routledge, 2003), p. 6.

[15] Leonid Zhmud, *The Origin of the History of Science in Classical Antiquity* (Berlin: De Gruyter, 2006), pp. 23–44.

[16] James G. Lennox, "The Disappearance of Aristotle's Biology: A Hellenistic Mystery," *Apeiron*, 1994, 27:7–24.

use of the word 'science' in the ancient context is wrong. The question of whether or not what they did is really science is fundamentally an ahistorical question and for the moment it is an unanswerable one."[17] As for the scientific disciplines: "Spheres of knowledge in antiquity were understood as having more fluid boundaries. Thus seeking or imposing modern disciplinary compartmentalization on ancient initiatives does violence to ancient thinkers and trivializes their accomplishments."[18] It is quite justifiable to warn against anachronism and urge that serious attention be paid to ancient Greek notions and conceptual categories. In practice, however, actors' categories, once declared, immediately give way to observers' categories (often very recent ones), for various pragmatic reasons.[19] What these reasons have in common is the logical and historical impossibility of explaining the ancient world—in this case, ancient science—using its own concepts and categories.[20]

In order to avoid the extremes of both views, we suggest another possibility. In studying ancient science, it seems much more productive not to abandon the modern disciplinary framework or to oppose it radically to the ancient but, instead, to compare them and identify areas where they differ and areas where they coincide, entirely or for the most part, or complement each other. From this perspective, it is fair to say that the ancient Greek division of "cognitive space," though different from the modern one, is closely related to it precisely in those areas where stable scientific disciplines (*mathēmata*) were established, distinct both from philosophy and from practically oriented *technai* (arts or crafts). Here we can provide only a very brief general outline of this complex problem, which cannot take into account important individual differences,[21] contradictory positions, inconsistencies in classifications, and so on.

The Greek language did not possess a term fully equivalent to our concepts "science," "*Wissenschaft*," and so on, which became common only in the mid-nineteenth century—as, indeed, it did not have general terms for art, religion, and culture. Lacking a general generic term, the Greeks used the names of the individual sciences and the species concept *mathēmata* (originally "branches of learning") or *mathēmatikai epistēmai*. A distinct group of four *mathēmata* (the future quadrivium)—geometry, arithmetic, astronomy, and harmonics—is first attested in the Pythagorean mathematician and philosopher Archytas (47 B 1 DK), a contemporary and friend of Plato, but goes back to an earlier time. Archytas considered these sciences to be related; from him this idea passed on to Plato and Aristotle and became firmly established in Greek culture. In the mid-fourth century B.C.E. this group of sciences, in which the application of mathematical methods was common, was joined by mechanics and optics.[22] This canonical set of

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[17] Tracey E. Rihll, "Introduction: Greek Science in Context," in *Science and Mathematics in Ancient Greek Culture*, ed. Tuplin and Rihll (cit. n. 9), pp. 1–21, on p. 8; see also Rihll, *Greek Science* (Oxford: Oxford Univ. Press, 1999), pp. 1–2.

[18] Georgia L. Irby, ed., *A Companion to Science, Technology, and Medicine in Ancient Greece and Rome* (Chichester: Wiley-Blackwell, 2016), p. 1.

[19] "For the purpose of this book, I have divided the subject matter into modern categories in spite of what I have said above": Rihll, *Greek Science* (cit. n. 17), p. 2. "The ancients did not compartmentalize their approach to the world, and we do so here only for the ease of organizing so large a project": Irby, ed., *Companion to Science, Technology, and Medicine in Ancient Greece and Rome*, p. 4. "We regularly map ancient practices onto modern categories, in order to be able to think about them at all": Keyser, "Name and Nature of Science" (cit. n. 13), p. 18.

[20] For very pertinent considerations on the problem in general see Nick Jardine, "Whigs and Stories: Herbert Butterfield and the Historiography of Science," *History of Science*, 2003, *41*:125–140; and Jardine, "Etics and Emics (Not to Mention Anemics and Emetics) in the History of the Sciences," *ibid.*, 2004, *42*:261–278.

[21] See, e.g., Geoffrey E. R. Lloyd, "The Pluralism of Greek 'Mathematics,'" in *The History of Mathematical Proof in Ancient Traditions*, ed. Karine Chemla (Cambridge: Cambridge Univ. Press, 2012), pp. 294–310.

[22] Arist. *Analytica priora* 76a25f., 79a6f., 79a24f.; *Phys.* 194a7–12; and *Metaph.* 1077a1–10, 1078a2–23. According to Aristotle, optics and mechanics depend on geometry and harmonics depends on arithmetic. See Richard McKirahan, "Aristotle's Subordinate Sciences," *British Journal for the History of Science*, 1978, *11*:197–220.

mathēmata survived with very minor variations until the end of antiquity. For example, according to Posidonius's student Geminus (first century B.C.E.), the author of an important encyclopedia of mathematical sciences often approvingly cited by Proclus, *mathēmata* included geometry, arithmetic, harmonics, astronomy, logistics, geodesy, optics, and mechanics.[23] Those engaged in these disciplines called themselves, and were called by others, *hoi peri mathēmata* or *hoi mathēmatikoi*.[24]

The term "*epistēmē*" ("knowledge," "scientific knowledge"), though often applied to what we call sciences, was much wider than that would suggest and could denote a philosophical discipline or a practical art. Aristotle, for example, distinguished three kinds of *epistēmai*: practical (politics, rhetoric), productive (music, poetry, manual arts), and theoretical, these last further subdivided into *theologikē* (metaphysics), *physikē* (natural philosophy), and *mathēmatikē*.[25] Originally, "*epistēmē*" and "*technē*" were used interchangeably, but from the time of late Plato and especially since Aristotle they began to be set up in opposition to one another as scientific knowledge, pursued for its own sake, and practically oriented art. This distinction was not consistently maintained, so that geometry and astronomy could be referred to as *technai*, yet in this case as *logikai*, *theorētikai*, or *semnai technai*, in contrast to *banausoi* or *praktikai technai* (base, manual crafts).[26] The ancient higher education curriculum, *enkyklios paideia* or *enkyklia mathēmata*, attested since the late Hellenistic period, included, along with grammar, dialectic, and rhetoric, four mathematical disciplines: geometry, arithmetic, astronomy, and harmonics.[27] Philosophy was regarded, with some exceptions, as the goal and culmination of *enkyklios paideia*, as the mistress of *enkyklia mathēmata*[28]—which, in their turn, depended on philosophical principles,[29] rather than being identified with them.[30] Even in the late period, when metaphysics, physics, and mathematics were considered not as independent though related *epistēmai*, as in Aristotle (*Metaph.* 1064b3), but as parts of philosophy, boundaries between them remained distinct (cf. the text leading up to note 34). More common, however, was the division of philosophy into logic, physics, and ethics.

Greek physics—that is, natural philosophy—covered most fields of knowledge related to the study of animate and inanimate nature, including physical but not mathematical astronomy. In a few fields of physics in its modern sense, such as harmonics, optics, and mechanics, the

[23] Procl. *In Eucl.*, 38.4–42.8. The presence of practical logistics and geodesy testifies to the Hellenistic origin of the scheme (on geodesy cf. Arist. *Metaph.* 997b26, b32). See also Alex. *In Arist. Topic*, 22.23f.; Asclep. *In Arist. Metaph.*, 363.7–20; Porph. *Vit. Plot.* 14; Procl. *In Eucl.*, 60.1f., 63.14f.; and David. *Proleg.* 60.9–65.7.

[24] For *hoi peri mathēmata* see Archyt. 47 B 1 DK; Archim. *De sphaer. et cyl.* I, 9.19, *De lin. spiral.* II, 8.10; Philo Alex. *De decalogo* 102, 3; Porphyr. *In Prol. Harm.* 88.29; and *Schol. in Arat.* 1091, 11, among others. References to *hoi mathēmatikoi* are too numerous to mention individually.

[25] *Metaph.* 1025b–1026a, 1063b36–1064b6; cf. *Phys.* 193 b 22–36. For more detail see Zhmud, *Origin of the History of Science in Classical Antiquity* (cit. n. 15), pp. 122–124.

[26] See, e.g., Galen. *Adhort. ad artes addiscend.* 14, 21; Sext. Emp. *Mat.* 2, 5; 11, 197; Ammon. *In Porph. Isag.* 9.6; Asclep. *In Arist. Metaph.*, 152.35–153.6; and Philop. *In Arist. Analytica priora*, 305.18.

[27] The best presentation of the evidence for the dating of the ancient higher education curriculum is H. Fuchs, "Enkyklios paideia," *Reallexikon für Antike und Christentum*, 1962, 5:365–398. See also Georg Rechenauer, "Enkyklios paideia," in *Historisches Wörterbuch der Rhetorik*, Vol. 2 (Tübingen: Niemeyer, 1994), pp. 1160–1185. Cf. Ilsetraut Hadot, *Arts libéraux et philosophie dans la pensé eantique* (Paris: Vrin, 1984).

[28] Aristo of Chios (*SVF* I, 350); Clem. Al. (*Strom.* I, 5, 30); and Rechenauer, "Enkyklios paideia," pp. 1170–1172. The idea derives from Plato, who regarded *mathēmata* as propaedeutic to philosophy (*Resp.* 531d, 536d).

[29] "But certainly everybody knows that philosophy gave to all individual sciences the principles and the seeds from which then apparently their theorems arose": Phil. Alex. *De congr. erud. gr.* 146–147.

[30] See Friedmar Kühnert, *Allgemeinbildung und Fachbildung in der Antike* (Berlin: Akademie, 1961), pp. 33–42; Fuchs, "Enkyklios paideia" (cit. n. 27), pp. 366–370; Hadot, *Arts libéraux et philosophie dans la pensé eantique* (cit. n. 27), Ch. 6, sects. 2, 3; and Rechenauer, "Enkyklios paideia" (cit. n. 27), pp. 1169–1172.

Greeks succeeded in isolating particular problems and raising their research to the scientific level by expressing the results of comparatively simple observations and experiments in mathematical form. Revealingly, according to ancient classification, these disciplines belonged not to physics but to *mathēmata*. From Aristotle to Simplicius, the difference between mathematics and physics was explained in the same way: a *mathēmatikos* concerns himself only with the unchangeable properties mentally separated from any natural objects, either unmoved (geometry and arithmetic) or in motion (astronomy, harmonics, etc.). Physics deals with substance, quality, and change of bodies, mathematics with their quantity, continuity, and the like.[31]

Greek philosophers always wanted to be distinguished from *mathēmatikoi*, regardless of whether they themselves engaged in *mathēmata*, like Posidonius, or willingly listened to the *mathēmatikoi*, like Plato and Aristotle, or rejected mathematics and the entire *enkyklios paideia*, like Epicurus.[32] Since the geometers and astronomers do not know how to make use of their discoveries, asserts Plato, those among them who are not utter blockheads must hand these discoveries over to the dialecticians, who will find a proper use for them (*Euthyd.* 290c). This sounds like a polemic against Archytas, according to whom it was the *hoi peri mathēmata* who reached a correct understanding of the nature of the universe and of particular things (47 B 1 DK). Obviously, Archytas did not need any intermediary to interpret the results of scientific research. Why, asks Aristotle, can a boy "become a mathematician, but not a philosopher (*sophos*) or a physicist (*physikos*)? Is it because the objects of mathematics are abstractions while the first principles of these other subjects come from experience, and young men have no conviction about the latter but merely use the proper language?"[33] *Mathēmatikoi* understandably had fewer chances to dispute philosophers' views, but when they did so—for example, Hero of Alexandria and Ptolemy in the prefaces to the treatises on mechanics and astronomy—they argued for the superiority of *mathēmata* over philosophy, first and foremost because of the certainty and indisputability of their methods: "The first two divisions of theoretical philosophy should rather be called guesswork than knowledge: theology because of its completely invisible and ungraspable nature, physics because of the unstable and unclear nature of the matter. . . . Only mathematics can provide sure and unshakable knowledge to its devotees, provided one approaches it rigorously. For its kind of proof proceeds by indisputable methods, namely arithmetic and geometry."[34]

Alchemy and astrology were never regarded as theoretical sciences (*epistēmai*). Alchemy, which for ancient cognitive culture was a very marginal field without even a proper name, appeared only in the mid-first century C.E. and considered itself a *technē* (in fact, *theia* or *hiera technē*), an art or craft dealing with recipes for transmuting metals into gold and silver; it was located at the intersection of natural philosophy, occult knowledge, and arts.[35] It seems that hardly anyone in antiquity regarded it as akin to a discipline such as geometry or optics.

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[31] Arist. *Phys.* 193b22–194a11. See Deborah Modrak, "Aristotle on the Difference between Mathematics and Physics and First Philosophy," *Apeiron*, 1989, 22:121–140; Diodorus of Alexandria (first century B.C.E.) *ap.* Achill. *Isagog*, 2.2–10; and Simpl. *In Arist. Phys.* 290.27–293.6. According to Posidonius, physics explains causes, while astronomy is a descriptive discipline; its various hypotheses attempt to "save the phenomena" without providing the true explanation of their causes (fr. 18 E.-K).

[32] For Epicurus's bitter criticism of Eudoxus's school see David Sedley, "Epicurus and the Mathematicians of Cyzicus," *Cronache Ercolanesi*, 1976, 6:23–54.

[33] *Eth. Nic.* 1142a16–19, trans. after W. Ross.

[34] Ptol. *Alm.*, 6.11–21, trans. G. Toomer. See Jacqueline Feke, "Meta-mathematical Rhetoric: Hero and Ptolemy against the Philosophers," *Historia Mathematica*, 2014, *41*:261–276. On the superiority of *mathēmata* over philosophy in Ptolemy's view see also Liba Taub, *Ptolemy's Universe: The Natural Philosophical and Ethical Foundations of Ptolemy's Astronomy* (Chicago: Open Court, 1993), pp. 25–26; and Jaap Mansfeld, *Prolegomena Mathematica: From Apollonius of Perga to Late Neoplatonism* (Leiden: Brill, 1998), pp. 66–69.

[35] F. Sherwood Taylor, "The Origin of Greek Alchemy," in *Alchemy and Early Modern Chemistry: Papers from* Ambix, ed. Allen G. Debus (Huddersfield: Mills, 2004), pp. 30–42; Jos Weyer, "Alchemie, antike," in *Alchemie: Lexikon einer hermetischen*

The status of astrology was also a matter of some dispute. Having emerged in the first century B.C.E. (the earliest Greek horoscope is dated to 62 B.C.E.) at a meeting point of scientific, philosophical, and religious traditions of Greece, Babylon, and Egypt, astrology was counted by its adherents as a *technē* (one could make a living from it) that used astronomical theory and data to predict future earthly events, individual or collective.[36] Some Greek astronomers, among them Ptolemy, found such practice acceptable; others ignored or disparaged it. A number of philosophical schools (Epicureans, Skeptical Academy, Pyrrhonians) and individual thinkers (Cicero) criticized astrology as false and useless, while others included it in their systems as a whole or in part.[37] Yet astrology never reached the epistemological status of astronomy, even from the perspective of its scientific adepts. Ptolemy, for example, drawing a distinction between astronomy and astrology, claimed that only those who are blind can criticize the former, while the latter is a far more conjectural *technē*, so that its pretensions to predict the future have to be carefully limited, explained, and defended.[38]

Therefore, in speaking of ancient science, it is fair to focus on the group of autonomous scientific disciplines, *mathēmatikai epistēmai*—in which we also include geography, in view of its fundamental kinship to astronomy and mathematics and in spite of its significant differences from them, its overlap with history, and other distinctive features.[39] Geographical science, fully developed by Eratosthenes (ca. 276–ca. 194 B.C.E.), was the last scientific discipline to emerge in antiquity; the others were established by the fourth century B.C.E.[40] Each discipline had its own name (*astronomia*, *arithmetikē*, *harmonikē*, *geōmetria*, *geōgraphia*, etc.), identical to the contemporary term, and its own subject area, partly overlapping with the subject of these disciplines in modern science. Each discipline had its own specialists (*astronomoi*, *arithmetikoi*, *harmonikoi*, *geōmetrai*, *geōgraphoi*, etc.), many of whom spent considerable time doing research and writing books, often in various genres and areas (the level of specialization

Wissenschaft, ed. Claus Priesner and Karin Figala (Munich: Beck, 1998), pp. 23–25; and Matteo Martelli, *Pseudo-Democrito: Scritti alchemici* (Paris: Archè, 2011), pp. 90–94.

[36] On astrology as a *technē* see Tamsyn Barton, *Ancient Astrology* (London: Routledge, 1994), pp. 6–7, 135–142. In addition to its own names, such as "apotelesmatics" (ἀποτελεσματική), "genethlialogy" (γενεθλιαλογία), "astromancy" (ἀστρομαντεία, ἀστρομαντική), "horoscopy" (ὡροσκοπία), etc., Greek astrology had two names in common with astronomy: *astrologia*, which originally meant the same thing as *astronomia*, and *mathēmatikē* (*technē*), so that since the first century C.E. astrologers were not infrequently called *mathēmatikoi*. See Simplicius's explanation of Aristotle's usage: "Since 'astromancy' had apparently not yet arrived in Greece, the ancients applied the name 'astrology' to what is now termed 'astronomy'; more recently people have made a distinction in terminology and have been calling the study that looks to the movements of the heavenly bodies 'astronomy' and they have given that which deals with the results of those movements—'astrology'—its own particular name" (*In Arist. Phys.*, 293.9–15, trans. B. Fleet). Cf. Wolfgang Hübner, *Die Begriffe "Astrologie" und "Astronomie" in der Antike* (Mainz: Akademie Mainz, 1989).

[37] For a good overview see Anthony A. Long, "Astrology: Arguments pro and contra," in *Science and Speculation: Studies in Hellenistic Theory and Practice*, ed. Jonathan Barnes *et al.* (Cambridge: Cambridge Univ. Press, 1982), pp. 167–192.

[38] *Tetr.* 1, 1–3. See, e.g., his attempt to distinguish between two kinds of astrology: "most, for the sake of gain, claim credence for another art in the name of this (ἑτέραν τέχνην τῷ ταύτης ὀνόματι), and deceive the vulgar, because they are reputed to foretell many things, even those that cannot naturally be known beforehand" (1, 2, 13, trans. F. Robbins). See Mark Riley, "Theoretical and Practical Astrology: Ptolemy and His Colleagues," *Transactions of the American Philological Association*, 1987, *117*:235–256; and Daryn Lehoux, *Astronomy, Weather, and Calendars in the Ancient World* (Cambridge: Cambridge Univ. Press, 2007), pp. 36–39. Otto Neugebauer, *A History of Ancient Mathematical Astronomy*, Pt. 2 (New York: Springer, 1975), p. 943, denied any direct influence of astrology on astronomy.

[39] On the independence of Greek mathematics from philosophy see, e.g., Wilbur R. Knorr, "Infinity and Continuity: The Interaction of Mathematics and Philosophy in Antiquity," in *Infinity and Continuity in Ancient and Medieval Thought*, ed. Norman Kretzmann (Ithaca, N.Y.: Cornell Univ. Press, 1982), pp. 112–145. On historical and geographical traditions in ancient geography see, e.g., Christiaan van Paassen, *The Classical Tradition of Geography* (Groningen: Wolters, 1957).

[40] Eudoxus of Cnidus and Dicaearchus (both fourth century B.C.E.) were the first to employ mathematical methods in geography. See Michele R. Cataudella, "Some Scientific Approaches: Eudoxus of Cnidus and Dicaearchus of Messene," in *Brill's Companion to Ancient Geography*, ed. Serena Bianchetti, Cataudella, and Hans J. Gehrke (Leiden: Brill, 2015), pp. 111–131.

depended on the discipline). These people were by no means professionals in the modern sense of the word: they were not trained in special educational institutions, held no scientific degrees, were not members of scientific corporations, and, most important, did not receive financial remuneration for their work (with the exception of practical mechanics).[41] However, most of them considered themselves to be scientists—in the Greek idiom, *mathēmatikoi*—and were regarded as such by others. These are the people that we are going to count.

III. FORMATION OF THE DATABASE: SELECTION CRITERIA FOR ANCIENT SCIENTISTS

The editors of *EANS*, "preferring errors of inclusion to those of exclusion," greatly expanded its chronological, geographical, and disciplinary boundaries.[42] *EANS* begins ancient science with Homer and Hesiod and ends in the 650s C.E. It also contains about 200 entries on authors who wrote in Armenian, Celtic, Gothic, Egyptian, Persian, Sanskrit, and Semitic languages. We decided to exclude anyone who falls outside the accepted chronological borders of ancient science (early sixth century B.C.E.–mid-sixth century C.E.), as well as those who wrote in languages other than Greek and Latin. An exception was made for the few cases where texts originally written in other languages were translated into Greek and Latin (e.g., Carthaginian *peripli*) or when references to Babylonian authors (Kidinnu, Naburianu) in Greek scientific texts suggest that an intercultural transfer of knowledge had indeed taken place (cf. Section VI, at note 66).

Further, for each discipline we counted only those persons who participated in *the production, dissemination, and preservation of scientific knowledge*. From this perspective, the novelty of the results is not crucial: an author of a didactic astronomical poem, a compilatory introduction to mathematics, a geographical compendium that preserved data of earlier, lost works, and so on, was classified as a scientist, in so far as the topics and problems of these writings do not go beyond the scope of a given discipline. Decisions about membership in the scientific community are much easier to make if a specialized scientific work by an author is known, the more so if it is preserved. But the lack of such a work—or, rather, the lack of information about it—is not grounds for exclusion (as is, indeed, the case in our own time as well). A person who taught mathematics to an outstanding scientist would be included, as would the colleague of a renowned mathematician to whom the latter dedicated his treatise. In some cases, we have more than enough evidence of belonging to a discipline—for example, if someone was called a "geometer" in a context that leaves little doubt about the nature of his occupation; in others, we possess very little. If any fact could clearly indicate the disciplinary affiliation of a person, the decision was made to count that person as a scientist. When a definite answer was not possible that person was excluded. This approach involved a careful reconsideration of all entries remaining after the nonscientific fields of knowledge were excluded. From the *EANS* list of ancient scientists we excluded philosophers, if evidence about their activities in the *mathēmata* is unavailable (on those who were active in philosophy and sciences see Section V, after note 57); historians, whose writings contain only brief geographical descriptions of places, which necessarily accompany any book in political or military history; paradoxographers, who were, without sufficient reasons, listed among geographers; and so on. On the other hand, we have included in the data base four names not listed in *EANS*, credited some scientists with an ad-

[41] On the difference between the specialization and professionalization of ancient scientists see Andre Laks, "Remarks on the Differentiation of Early Greek Philosophy," in *Philosophy and the Sciences in Antiquity*, ed. Robert W. Sharples (Aldershot: Ashgate, 2005), pp. 8–22, esp. pp. 15–18.

[42] Keyser and Irby-Massie, eds., *Encyclopedia of Ancient Natural Scientists* (cit. n. 12), p. 2.

ditional discipline (e.g., recognizing that a mathematician also contributed to astronomy), and, finally, changed 93 datings on the basis of alternative biographical sources.

Selection criteria for mechanics, geographers, and harmonic scientists require additional explanation. Mechanics is not only a theoretical but also a practical science, related to technology and inventions, and so it was in antiquity. According to Geminus, mechanics, besides its theoretical part, also included the art of making engines of war, which Archimedes devised, mechanisms moved by wind, described by Ctesibius, and celestial spheres, which Archimedes also dealt with.[43] Hero divided the science of mechanics into a theoretical and a practical part, while Pappus regarded mechanics as both a science and an art.[44] The mathematical core of ancient mechanics was surrounded by a broad and varied practical periphery. It would be wrong in principle to restrict mechanics to theory; even in the work of the most scientific of Greek mechanics, Archimedes, theory and practice are deeply interconnected. (In this regard, it is worth noting that work to reconstruct the astronomical Antikythera mechanism has demonstrated the integration of ancient science and technology to an extent that we previously could only have guessed at.)[45] Yet to count all the inventors of military devices as scientists would also be a mistake. Therefore, we include among the mechanics only those engineers and inventors whose work implies a scientific (mathematical) component.

Ancient geography, like modern geography, consisted of several subdisciplines: theoretical geography, which, according to Strabo and Ptolemy, was based on a mathematical method;[46] and a descriptive discipline sometimes called chorography (regional geography).[47] Representatives of the former, as a rule, also engaged in mathematics and astronomy (Eudoxus, Eratosthenes, Hipparchus, Posidonius, and so on); the latter, much more populous, was represented mainly by descriptive works dealing with different parts of the ecumene (Egypt, Asia Minor, Sicily, India, and so on) that offered empirical data about cities, regions, rivers, and seas, about the distances between them, and so forth.[48] Since theoretical geography was based directly on such descriptions, particularly those containing numeric data, their authors have also been included in our list—the more so since, well into modern times, geography fed on reports by travelers, sailors, merchants, and the like, who were not immediately interested in its development as a mathematical science. Where relevant, we shall treat these two categories separately.

Harmonics has historically consisted of two major branches: the mathematical, which originated in the Pythagorean school and was shaped by Archytas; and the empirical, the main representative of which was Aristoxenus of Tarentum, a student of the Pythagoreans and then of Aristotle. For the most part ancient musical theorists adhered to one of these traditions and criticized or ignored the other. Nonetheless, in some respects the two branches were mutually dependent, and at the end of the Hellenistic period attempts (some of them successful) were made to reconcile them. In many authors of late antiquity the two traditions coexisted, but only

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[43] Gemin. *ap.* Procl. *In Eucl.*, 41.2f.

[44] Papp. *Synag.* Bk. 8, pp. 1022–1024. See Sylvia Berryman, *The Mechanical Hypothesis in Ancient Greek Natural Philosophy* (Cambridge: Cambridge Univ. Press, 2009), p. 49.

[45] See the Antikythera Mechanism Research Project: www.antikythera-mechanism.gr/project.

[46] See Hipparch. fr. 34 Dicks; Strab. 1, 1, 13 and 20–21 (geography depends on geometry and astronomy); 2, 1, 41 (Eratosthenes was too mathematical for Strabo's taste; cf. 2, 2, 1 on Posidonius); 2, 5, 1–2 (geographers should rely on geometers, geometers on astronomers, and the latter in their turn on physicists [this is Posidonius's view]); and Ptol. *Geog.* 1, 1, 3–6.

[47] Klaus Geus, "Progress in the Sciences: Astronomy and Hipparchus," in *Brill's Companion to Ancient Geography*, ed. Bianchetti *et al.* (cit. n. 40), pp. 150–160, esp. pp. 150–152. Of course, this theoretical/descriptive dichotomy does not exhaust the whole variety of ancient geographical literature; see Wolfgang Hübner, ed., *Geographie und verwandte Wissenschaften* (Stuttgart: Steiner, 2000).

[48] On chorography see Strab. 1, 1, 16; 2, 4, 1; 2, 5, 1; 2, 5, 17; 5, 2, 7.

Ptolemy managed to achieve their true synthesis on the basis of mathematical harmonics.[49] In view of this, our already short list of harmonic scientists includes representatives of both branches, nearly half of whom also engaged in other exact sciences.

IV. NUMBER OF SCIENTISTS AND THEIR DISCIPLINARY AND TEMPORAL DISTRIBUTION

In our count, as compared to that of *EANS*, the total number of ancient scientists has decreased fivefold, to 407 from 2,043.[50] These 407 scientists are distributed across the disciplines as follows (the same person could do several sciences):

Geography 137
Astronomy 129
Mathematics 127
Mechanics 57
Harmonics 35
Optics 19

Their distribution over time is given in Figure 3, which presents a summarizing curve for all ancient scientists; it shows two peaks of 66 contemporaries in 325 and 225 B.C.E. and one more of 70 in 100 B.C.E.

Speaking quantitatively, five distinct stages can be distinguished in the development of ancient science: initial growth (sixth–mid-fourth centuries B.C.E.), flourishing (mid-fourth–mid-first centuries B.C.E.), rapid decline (second half of the first century B.C.E.), long stagnation (first–fifth centuries C.E.), and eventual extinction (sixth century C.E.). A historian of ancient science interested in its overall evolution would immediately recognize familiar patterns behind these quantitative data. Before considering the dynamics of the development of science in general, however, let us briefly discuss each constituent discipline. Geography turned out to be the most populous (137 names), undoubtedly owing to the numerous descriptive works that were produced. Not surprisingly, both peaks in the number of ancient scientists coincide exactly with the peaks in geography (see Figure 4). The first peak in geographers (21 names) came in 350–325 B.C.E. and was connected with the campaigns of Alexander the Great, which rapidly expanded the borders of the ecumene; the second (27 names) came in the first century C.E., when Hellenistic states became part of the sprawling Roman republic.

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[49] Andrew Barker, *Scientific Method in Ptolemy's "Harmonics"* (Cambridge: Cambridge Univ. Press, 2000); and Barker, *The Science of Harmonics in Classical Greece* (Cambridge: Cambridge Univ. Press, 2007).

[50] Our data set was represented by a CSV file containing 407 entries on individual scientists as well as anonymous and pseudonymous treatises. Each entry was characterized by a number of attributes: scientist's name or the title of a treatise, dates of birth and death (where known), scientific disciplines to which a given scientist contributed (a series of six binary variables for astronomy, harmonics, geography, mathematics, mechanics, and optics), and a dummy variable to distinguish mathematical and purely descriptive geographers. Most dates for persons and writings used in this analysis are calculated approximately; sometimes they are rounded to decades and even centuries. Owing to the nature of the data, in 59 of the 407 cases (14.5 percent) the calculated lifespan exceeded the natural limits of human life (spanning from 120 through 660 years), but this does not affect the major trends discussed below. Further, a series of time slices (subsets of the original data set) was created with an increment of 25 or 50 years, depending on a particular task. The numeric vectors for time series were built by counting names or summarizing binary variables for disciplines in each time slice. It should be noted that lifespans, not assumed periods of scientific productivity, served as the basis for calculations. This means that two scientists belonging to one and the same time slice do not necessarily belong to the same generation or to the same age cohort. All data transformations, calculations, and original figures were made using standard functions of R, a language and environment of statistical programming: R Core Team, *R: A Language and Environment for Statistical Computing* (Vienna, 2015), http://www.R-project.org.

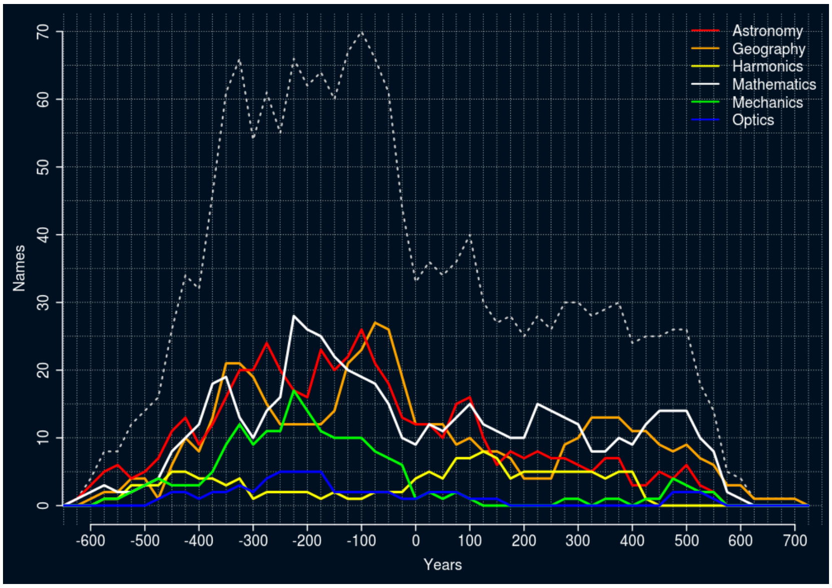

Figure 3. Chronological and disciplinary distribution of ancient scientists.

The rise of descriptive geography in the fourth–fifth centuries C.E. is due to the large number of Roman geographical writings, often subordinated to the tasks of imperial administration. Geographers who were also recognized as mathematicians and astronomers (i.e., authors of treatises in mathematical geography) were far less numerous than geographers in general, making up 20 of 137, which works out to 1 in 7 (see Figure 4). If we consider only this group, geography is no longer the largest discipline but nearly the smallest—though there is no appreciable change in the overall pattern of ancient scientific development. The first golden age of theoretical geography falls in 325–275 B.C.E., when enough empirical evidence for its theoretical reflections had been accumulated; after 400 C.E. mathematical geography ceased to exist.

Mathematics (see Figure 5), third in the number of scientists (127 names), shows a very rapid pace of development in 475–350 B.C.E. (more than a fivefold increase) and reaches its first peak (19 names) in 350 B.C.E., still in the pre-Alexandrian period. Such a concentration of names may be partly due to the fact that Eudemus of Rhodes, mentioned above, wrote a detailed *History of Geometry*, which featured many mathematicians of the fourth century B.C.E., including some not mentioned elsewhere. The second possible factor is the school of Eudoxus in Cyzicus, founded circa 362 B.C.E., one of the very few mathematical schools known to us.[51] After a relative decline around 300 B.C.E., the number of mathematicians rose again, reaching its maximum (28 names) in 225 B.C.E. (during the lifetime of Archimedes and Apollonius of Perga). Later on, decline alternated with rise, while the number of mathematicians fluctuated around 10–15, including in 50 C.E. The final decline in mathematics began later than that in other sci-

[51] Zhmud, *Origin of the History of Science in Classical Antiquity* (cit. n. 15), pp. 166–213. The school of Eudoxus included four Cyzicenes—Callippus, Polemarchus, Athenaeus, and Helicon—Amyclas of Heraclea, Menaechmus, Dinostratus, Theudius of Magnesia, and, possibly, Hermotimus of Colophon. If, as is very probable, Polyaenus of Lampsacus (ca. 340–ca. 285 B.C.E.), whom Epicurus succeeded in winning to his side, also belonged to Eudoxus's school, then it was the only scientific school that lasted for three generations. See Sedley, "Epicurus and the Mathematicians of Cyzicus" (cit. n. 32); Netz, "Classical Mathematics in the Classical Mediterranean" (cit. n. 8), pp. 7, 11–12; and Zhmud, *Origin of the History of Science in Classical Antiquity*, pp. 99–100, 284. On Apollodorus Logistikos of Cyzicus (?) see 74 *DK*; *FGrHist* 1097; and Zhmud, *Pythagoras and the Early Pythagoreans* (cit. n. 11), pp. 267–268.

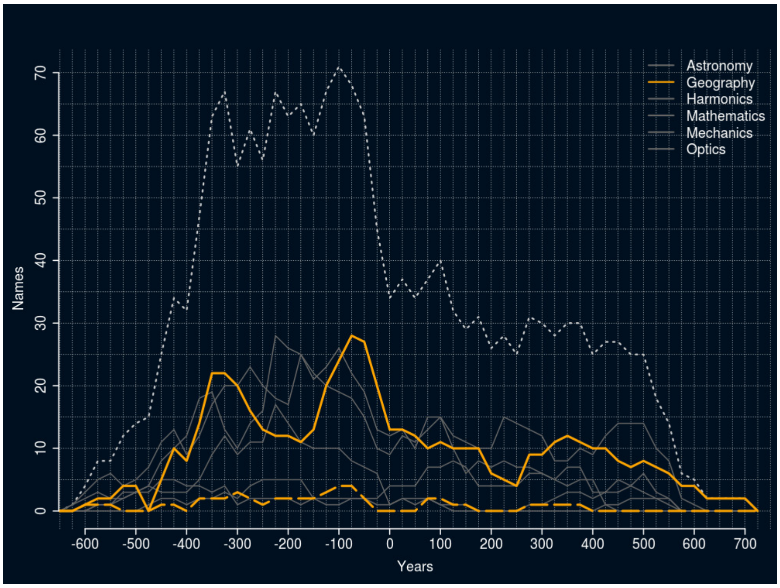

Figure 4. Descriptive and theoretical geography.

ences, around 500 C.E.; this delay is related to an active (though not very productive, in terms of new results) involvement in mathematics on the part of the Neoplatonic schools of Athens and Alexandria (see Section V, after note 62). More than half of the fifth-century mathematicians worked in these two cities.

Astronomy (see Figure 5), with practitioners almost equal in number to the mathematicians (129 names), developed at a slower rate and reached its heyday only in the Hellenistic period, with three distinct peaks at 275, 175 (the time of Hipparchus), and 100 B.C.E. (23–26 names).

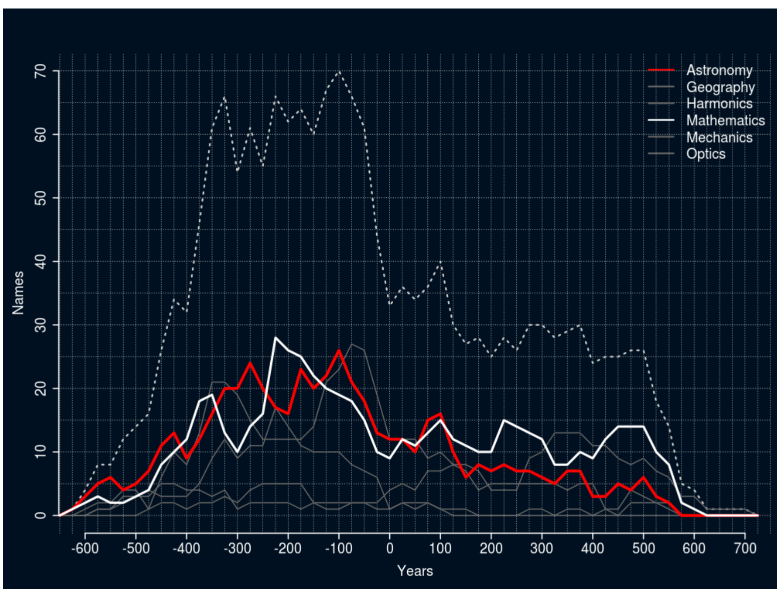

Figure 5. Mathematics and astronomy.

After 50 B.C.E. it declined rapidly, and then more slowly but steadily, until 50 C.E.; it rose again in 50–125 C.E. (this preceded the start of the active career of Ptolemy, who was born ca. 100 C.E.). Interestingly, for almost six hundred years (450 B.C.E.–125 C.E.), the number of contemporary astronomers, with a single exception around 400 B.C.E., when there were only 9 names, never fell below 10. Astronomy slowly faded away at the end of the sixth century.

Mechanics (see Figure 6) developed very slowly in 500–375 B.C.E. (fewer than 5 names on average), then experienced a rapid rise and reached its first peak around 325 B.C.E. (12 names). The full flourishing of mechanics fell entirely in the Hellenistic period, with its highest peak (17 names) in 225 B.C.E. (during the lifetime of Archimedes), coinciding with the second peak of mathematics. Up to 75 B.C.E. the number of mechanics regularly exceeded 10, but after 25 B.C.E. it declined sharply, dropping to almost none at the turn of the millennium. During the following centuries mechanics was barely kept alive, sometimes disappearing for long periods, as in 125–250 C.E.

The number of known specialists in harmonics and optics generally ranged from 0 to 5 (see Figure 6). In contrast to the other sciences, harmonics and optics show no marked peaks. Both small upticks in the harmonics curve coincided with the lifetimes of its major theorists. Archytas and Aristoxenus, who created the two main branches of harmonics, were active during the first optimum period (475–325 B.C.E.). Ptolemy, who synthesized their theories on the basis of Archytas's mathematical harmonics, was active during the second (75–150 C.E.), when the number of contemporary harmonic scientists for the first (and only) time slightly exceeded 5. After 400 C.E. harmonics declined rapidly.

The total number of specialists in optics was roughly half that of the harmonic scientists (19 vs. 35); this easily explains the curve of the development of optics, which holds pretty steady between 0 and 5. Most important advances in optics were achieved fairly early and were formulated by Euclid (note the small hump ca. 325 B.C.E.); the small number of specialists in optics in the following centuries correlated with the lack of tangible progress in the discipline. In 150–450 C.E. there was a major break; a weak elevation in late antiquity is related to the final codification of earlier achievements.

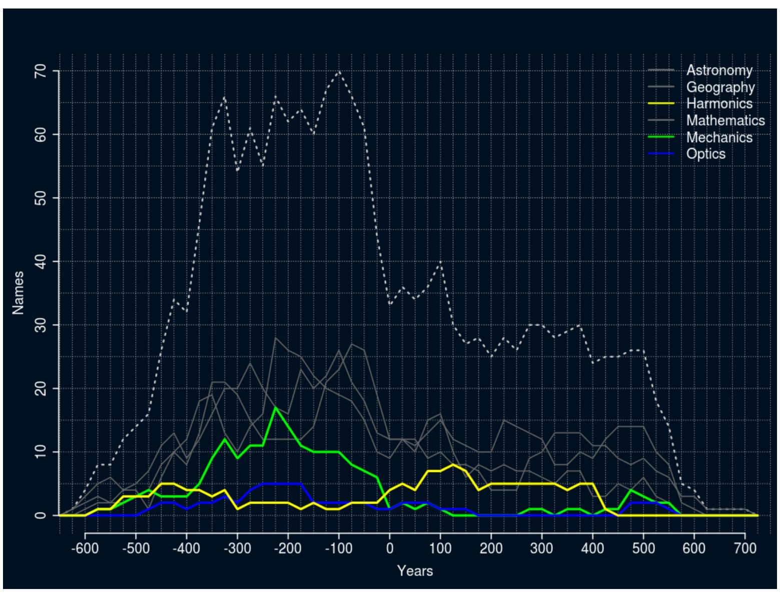

Figure 6. Mechanics, harmonics, and optics.

V. SOME COMPARISONS

Comparing our data on the dynamics of ancient science with other scholars' results, one can note a considerable similarity between the basic stages, though our findings allow for a more nuanced picture of historical dynamics than the preceding studies. Thus, according to Netz (as discussed earlier), the absolute maximum number of practicing mathematicians falls in the same period as our first peak (350 B.C.E.); his count, however, is somewhat lower (15 names). Further, Netz's graph shows an exceptionally deep recession running from 50 B.C.E. to 50 C.E., when the number of mathematicians dropped from 5 to 0. Our data reveal a pattern of much more stable development.[52]

In Kroeber, the beginning of the culminating phase of Greek science (310 B.C.E.) practically coincides with what we have designated (325 B.C.E.), whereas its end (120 B.C.E.) differs from our dating of the rapid decline of all the sciences (ca. 50 B.C.E.) by only seventy years (or even less, if we take only theoretical—and not practical—geography into consideration).[53] Since Kroeber's approach was to some extent qualitative and selective, based on the activities of 83 eminent scientists ranked according to their importance, the close match with our results is especially valuable. In particular, it supports a correlation between the most densely populated periods in each discipline and its highest achievements, which is already visible from the fact that the greatest Greek scientists—Archytas, Theaetetus, Eudoxus, Archimedes, Apollonius, Ptolemy—lived during or very close to the peaks of their respective sciences. We may infer, therefore, that the periods when the number of scientists grew rapidly, reached their high points, or stayed at a high level were times when the most prominent scientists lived and the most important discoveries were made—and vice versa.

Especially instructive in this respect is a comparison with the dynamics of discoveries and inventions calculated by Sorokin and Merton. Justifying his choice of a particular discovery, regardless of its relative importance, as a unit of measurement, Sorokin remarked that periods of the most numerous and the most important discoveries generally coincide, because every significant discovery is followed by dozens of others, whereas a trivial one is unproductive.[54] Sorokin's picture of the total number of inventions and discoveries, with its sharp second peak falling in the first century C.E. (see Figure 1), shows no apparent similarity to our picture. But if one takes into account only discoveries in mathematics and astronomy and compares them to our data on these sciences, the connection between the number of scientists and their gross productivity looks surprisingly strong (see Figure 7).[55] To put it simply, an increase of seven *mathēmatikoi* led to one additional discovery. Intuitively, this is what one would expect: the more scientists, the more discoveries, the more need to integrate them.

So: 407 known scientists over eleven centuries, half of them concentrated within the first two centuries of Hellenism—Is this many or few? In the postindustrial global era this number is equivalent to just one medium-sized scientific institution, such as ETH Zurich or Cold

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[52] Though any selection is unavoidably subjective, it should be noted that Netz begins Greek mathematics quite late, ca. 450 B.C.E., and ends a century earlier than usual, ca. 450 C.E., with the result that a number of important figures are not taken into account.

[53] *Pace* Kroeber, *Configurations of Culture Growth* (cit. n. 5), p. 104, this phase was not followed by a period of quantitative growth (120 B.C.E.–120 C.E.).

[54] Sorokin, *Social and Cultural Dynamics* (cit. n. 4), pp. 126–127.

[55] To extract a numerical vector used to build this graph and to calculate the Pearson's correlation, we needed a different set of time slices: the pace of time series was widened (from 25 to 50 years); and when counting the scientists' names, an overlap between mathematicians and astronomers was taken into account. Pearson's correlation between the number of mathematicians and astronomers (based on our data set) and the number of mathematical and astronomical discoveries (based on the data used by Sorokin and Merton) turned out to be 0.646 (p=0.0093).

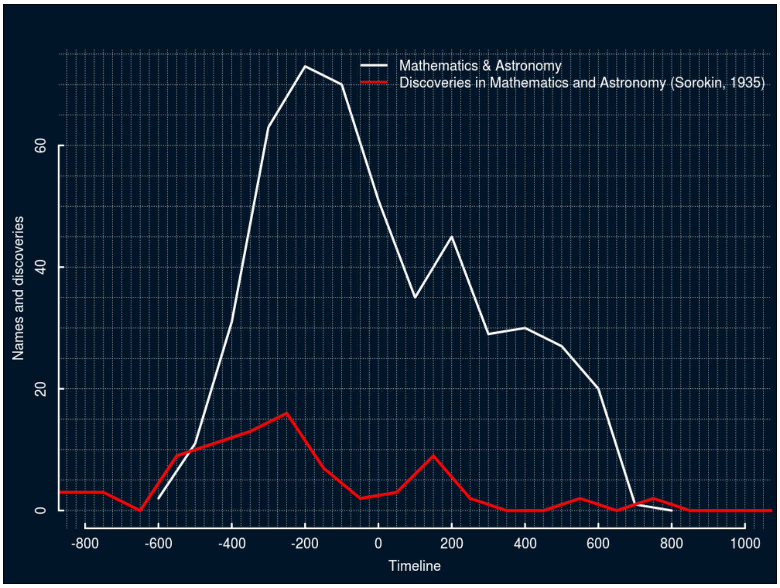

Figure 7. Ancient mathematicians/astronomers and their discoveries.

Spring Harbor Laboratory in New York. For a meaningful assessment of the "size" of Greek science, however, Renaissance Italy provides a far better object of comparison, both in terms of its population (about 11 million in 1500) and in terms of the type of science practiced.[56] According to data kindly communicated to us by Elio Nenci, Professor of the History of Science at the University of Milan, roughly 210–230 scientists worked in fifteenth- to sixteenth-century Italy in mathematics, mathematical astronomy, harmonics, optics, mechanics, and geography; the majority of them wrote elementary books on arithmetic (*abaco*), astronomy (*sphaera*), and the like.[57] This provides a pretty close match with the 183 scientists known from an equally flourishing period of Greek science (325–100 B.C.E.). Bearing in mind the better availability of the Renaissance sources, especially printed ones, it is entirely plausible to assume that in terms of the number of scientists the Hellenistic world was ahead of early modern Italy.

No less revealing is the comparison between the number of ancient scientists—407—and ancient philosophers—2,463, according to Goulet.[58] A sixfold difference reflects epistemological and, even more, social differences between science and philosophy in the ancient world. A philosopher could not boast of providing a generally acknowledged solution to some specific problem; rather, he explained to those interested the world of nature and the cosmos beyond it, interpreted and criticized social norms, taught followers how to be virtuous and how to seek happiness, and addressed both lofty religiousness and natural skepticism. Philosophers were

[56] M. H. Hansen, one of the leading authorities on Greek history, estimates the population of ancient Greek city-state culture ("from Spain to Caucasus and from Crimea to Libya") before the conquest of Alexander the Great (334 B.C.E.—i.e., ten years before our first peak in 325 B.C.E.) as between 7.5 and 10 million; see Mogens Herman Hansen, *The Shotgun Method: The Demography of the Ancient Greek City-State Culture* (Columbia: Univ. Missouri Press, 2006), pp. 32–34. There is, however, considerable scope for disagreement on the issue. For a much more modest estimate—ca. 5 million in the fourth century B.C.E.—see Walter Scheidel, "Demographic and Economic Development in the Ancient Mediterranean World," *Journal of Institutional and Theoretical Economics*, 2004, *160*:743–757, esp. p. 747.

[57] Personal email from Elio Nenci, 1 July 2016. This number includes the foreign mathematicians who lived in Italy for a time—e.g., Regiomontanus, Clavius, etc.

[58] But see note 11, above, regarding the Pythagoreans among Goulet's philosophers.

an integral part of the self-conception of ancient society, in which scientists occupied a much more modest place. Besides, ancient philosophers showed a much greater aptitude for self-organization and institutionalization than scientists (the same is also true for ancient doctors, who developed a certain institutional structure as early as the fifth century B.C.E.). Informal philosophical schools appeared as early as the sixth–fifth centuries B.C.E. (Milesians, Pythagoreans, Eleatics, Atomists); the fourth century B.C.E. witnessed the rise of the institutionalized philosophical schools (Academy, Lyceum, Stoa, Garden, and the like), which soon, along with the rhetorical schools, became the principal centers of higher education and in the imperial period were even state supported. Indeed, according to Goulet's estimate 71 percent of the ancient philosophers we know about belonged to the eight major philosophical schools. In Greek science even an informal school with a life span of at least three generations was quite a rare phenomenon;[59] scientific education existed only on the personal level; and state support of nonutilitarian research was limited to the Alexandrian Museion, which itself was not a specifically scientific but, rather, a cultural institution.[60] All these social differences usually go unnoticed by those who claim that science and philosophy were not differentiated in antiquity or were differentiated very late.

In fact, ancient scientists and philosophers represent neighboring and partly overlapping communities. The level of philosophers' participation in scientific activities, as well as the number of scientists who also engaged in philosophy (it is not always possible to distinguish between them), mostly fluctuated in the range of 10–15 percent, never falling below 7 percent (see Figure 8). This corresponds neatly to the 13 percent of philosophers among the reputed mathematicians and astronomers born between 1500 and 1600.[61]

Three periods in this diagram are worthy of notice. First, from the time of Thales (early sixth century B.C.E.) the share of philosophers among scientists diminished steadily, before stabilizing at the level of 15 percent in 450–300 B.C.E. Second, in 300–100 B.C.E., the most productive and populous period for Greek science, this share dropped below 10 percent and remained at the lowest level, which reflected growing specialization of all the disciplines, on the one hand, and the abandonment of the positive attitude toward *mathēmata* by the leading philosophical schools of the time, on the other. This is what stands behind the "divorce of science and philosophy" during Hellenism, though the notion of "divorce" should be taken metaphorically, if only because even in the period of their supposed "marriage"—for example, in the fifth century B.C.E.—the share of philosophers involved in *mathēmata* was about 15 percent, whereas in the first–second centuries C.E. it grew again, reaching 33 percent in 125 C.E.[62] The latter growth may be related to the scientific activities of the Middle Platonists and Neopythagoreans. Third, in late antiquity, between 400 and 550 C.E., philosophy and science formed a new al-

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[59] Netz, "Greek Mathematicians" (cit. n. 9), pp. 215–216. On Eudoxus's school see note 51, above. Among the Pythagoreans we are aware of several sequences with two generations each, including Pythagoras and his student Hippasus; Theodorus and Philolaus (both born ca. 470), whose teachers are unknown; and Archytas (born ca. 435/430), whose teacher is also unknown. Theaetetus and Eudoxus were students of Theodorus and Archytas, respectively, without being Pythagoreans. The mathematician Thymarides of Tarentum may have belonged to Archytas's circle. See Zhmud, *Pythagoras and the Early Pythagoreans* (cit. n. 11), pp. 119–131.

[60] Peter Marshall Fraser, *Ptolemaic Alexandria*, Vols. 1–3 (Oxford: Oxford Univ. Press, 1972), pp. 305–335. On the lack of institutions for theoretical mathematics see Markus Asper, "The Two Cultures of Mathematics in Ancient Greece," in *The Oxford Handbook of the History of Mathematics*, ed. Eleanor Robson and Jacqueline Stedall (Oxford: Oxford Univ. Press, 2009), pp. 107–132, esp. pp. 125–128.

[61] This statistic comes from *MacTutor History of Mathematics*: www-history.mcs.st-and.ac.uk.

[62] For the "divorce of science and philosophy" see, e.g., Charles Singer, *A Short History of Science to the Nineteenth Century* (Oxford: Oxford Univ. Press, 1941), p. 56. Often a lack of interest in *mathēmata* among Hellenistic philosophers is what is meant by "divorce."

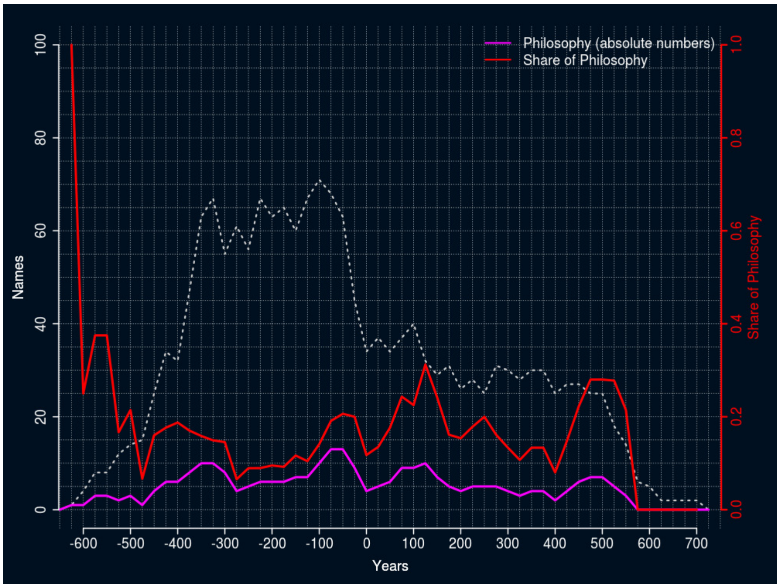

Figure 8. Ancient philosophers engaged in *mathēmata*.

liance, with the share of philosopher-scientists reaching 28 percent at its peak. Most of them belonged to the Neoplatonic schools of Athens and Alexandria, which provided an important milieu for *mathēmata* in their final phase—codification of received knowledge, encyclopedic projects, editing, commentaries, and the like.

VI. SCIENTIFIC CENTERS

When seen from the modern perspective, ancient science often appears as a kind of science where something went wrong, such that it did not develop as consistently as modern science and, accordingly, did not reach the level of Newtonian science.[63] Such an approach risks losing sight of the fundamental fact that in the wide historical perspective it is the growth of modern science, rather than the course of ancient science, that is exceptional. Kroeber's empirical study of the course of science in all civilizations where it existed revealed the same basic configuration: growth, maturity, decline, and decay (or, alternatively, revival). Later Ben-David would explain why, as Cohen phrased it, "Western science as we know it constitutes a major anomaly," having demonstrated how scientific leadership shifted from Italy in the sixteenth century to England in the seventeenth century, to France around 1800, to Germany in the mid-nineteenth century, and to America in the early twentieth century, with additional important actors such as the Netherlands and Russia.[64] Indeed, it is easy to see that this ongoing scientific race, with a new leader replacing a frontrunner whose capacities are exhausted, this pan-European and then worldwide competition of a dozen countries, large and small—that this is exactly what ensured the consistent development of Western science. If we compare this picture with Greek science, we immediately notice its tragic solitude: it did not have any con-

[63] H. Floris Cohen, *The Scientific Revolution: A Historiographical Inquiry* (Chicago: Univ. Chicago Press, 1997), pp. 241–260, offers a critical overview of the scholarly discussions on the principal shortcomings of Greek science.

[64] Kroeber, *Configurations of Culture Growth* (cit. n. 5), pp. 204–211; Cohen, *Scientific Revolution*, p. 254; Ben-David, *Scientist's Role in Society* (cit. n. 2); and Robert Gascoigne, "The Historical Demography of the Scientific Community, 1450–1900," *Social Studies of Science*, 1992, 22:545–573.

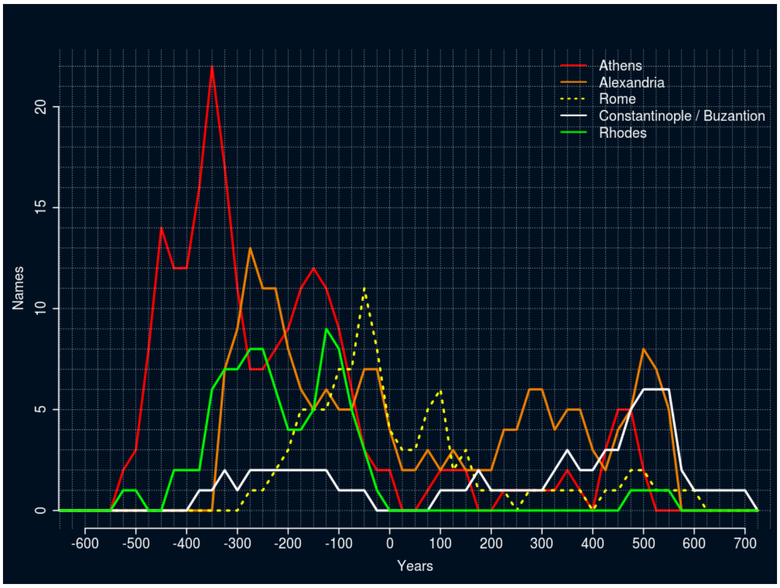

Figure 9. Major centers of Greco-Roman science.

temporary rivals to compete with or to be continued by.[65] This is what Ben-David disregarded while presenting Greek science as contrasting with Western science, rather than as an example of isolated European science. Greek astronomy, when it became sufficiently mature, appropriated the results of Babylonian astronomers, in spite of a severe language barrier, thus revolutionizing the whole discipline.[66] Yet Greek science remained completely alien to ancient Egyptians, Persians, Babylonians, Gauls, Germans, and Thracians, except for those few individuals who engaged in *mathēmata* inside the Greek world.[67] Even Romans who borrowed Greek poetry, drama, history, philosophy, and medicine mostly ignored Greek *mathēmata*, with the exception of descriptive geography.[68] Arabs, the true successors of ancient Greek science, appeared at a stage where it had long been dead.

Therefore, we cannot reasonably expect ancient science to have developed consistently in splendid isolation for a period much longer than it actually did. What we can expect is that Greco-Roman science experienced the same shift in scientific centers that we observe in the modern period—and this is exactly the case.[69] Five major centers of science—Athens, Alexandria, Rhodes, Rome, and Byzantium/Constantinople (see Figure 9)—along with lesser sites, appear and replace each other in a way similar to what we see with the leading centers of modern science.

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[65] Internal rivalry is discussed in Section 7, after note 84.

[66] Neugebauer, *History of Ancient Mathematical Astronomy* (cit. n. 38); and Alexander Jones, "The Adaptation of Babylonian Methods in Greek Numerical Astronomy," *Isis*, 1991, 82:441–453.

[67] See Netz, "Classical Mathematics in the Classical Mediterranean" (cit. n. 8), p. 199. Babylonian and Greek astrology influenced Egyptian astrology.

[68] Among 38 authors writing in Latin (36) or in Greek but who were undoubtedly of Roman origin (2), 23 dealt with geography, 9 with astronomy, 5 with mathematics, 4 with harmonics, and 3 with mechanics (see two indexes in Keyser and Irby-Massie, eds., *Encyclopedia of Ancient Natural Scientists* [cit. n. 12], pp. 1022–1026). A Roman name in itself is not sufficient grounds for considering 9 other individuals who wrote in Greek—among them Geminus of Rhodes, Serenus of Antinopolis, and Simplicius of Cilicia—to have been scientists of Roman origin.

[69] We understand "scientific centers" to mean cities that attracted scientists born elsewhere to reside permanently, to come periodically, or to pay a short visit. Our sources do not always allow us to make these distinctions.

After Miletus and Samos lost their leading positions (at 550 and 450 B.C.E., respectively), Athens began its very rapid rise, with an unprecedented peak of 22 scientists around 350 B.C.E.[70] In the classical period, Athens was the only major center of science; even after a sharp recession during early Hellenism, caused by political factors, it remained at a higher level than its competitors. Late Hellenistic Athens was plundered by Sulla (88 B.C.E.) but managed to survive as a cultural center. The rise of Rhodes began somewhat later; it was an important regional center, yet far less politically powerful than Athens and Alexandria. During Hellenism it experienced two noticeable peaks, then rapidly declined, collapsing completely after being sacked by Cassius's army (43 B.C.E.). Alexandria's turn came next: it swiftly superseded Rhodes and early Hellenistic Athens, reaching the level of 11–13 scientific contemporaries in 275–225 B.C.E., and even after losing its leading position it remained a major scientific center until the end of antiquity. Contrary to what is usually assumed, scientists associated with Alexandria (61, or 15 percent) are less numerous than those associated with Athens (76, or 18.7 percent). The years from 300 to 50 B.C.E. saw the most active and productive competition between Athens, Alexandria, Rhodes, and Rome. At the end of the second century B.C.E. Rome became an attractive center for scientists, most of whom were not Romans by birth. Rome's abrupt decline was even more spectacular than its rise. Byzantium kept a very low profile before being renamed Constantinople (330 C.E.); it started to play a significant role as a capital of the Roman Empire, competing in 450–550 C.E. with Alexandria and Athens.

The exceptional mobility of Greek poets, artists, philosophers, and scientists is well known.[71] In our study it is illustrated by the low proportion of scientists born and active in the respective cities in the time of their flourishing as principal scientific centers: 2 of 22 in Athens during 400–300 B.C.E., 5 of 18 in Alexandria during 325–150 B.C.E., 4 of 12 in Rhodes during 375–200 B.C.E., and 2 of 10 in Rome during 125–1 B.C.E. In every case newcomers and foreigners constituted the overwhelming majority. What tempted them was not specific scientific institutions where they could pursue their careers (those few who worked at the Alexandrian Museion were appointed by the Ptolemies), but the opportunity to be in contact with people of a similar background, find teachers or students, buy books, visit private and public libraries, or—if they were engineers—find wealthy sponsors.[72] Wealth and power were also important factors: four of the five major centers—Athens, Alexandria, Rome, and Constantinople—were capitals of mighty and wealthy empires, and Rhodes too was a very rich commercial city.

Going beyond the five principal centers of scientific activity, we find six secondary ones: Cyzicus (15 names), Miletus (14), Syracuse and Samos (11 each), Antioch (10), and Cyrene (9). Taken together, these eleven centers sheltered 217 (53.3 percent) of all the ancient scientists; the birthplace or workplace of 106 scientists (i.e., about a fourth of the total) is unknown. We can present a more polycentric (though far from precise) map of ancient science by dividing ancient scientific history into three main periods (cf. Figure 3), which more or less coincide with ancient historical periods—archaic/classical, Hellenistic, and imperial/late antique—and identify all the cities associated with at least three scientists during each period.[73]

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[70] The peak can be accounted for in part by the bias in our sources: half of the scientists attested for fourth-century Athens figure in Eudemus's histories, noted earlier, and half of the latter group belong to the school of Eudoxus, who came from Cyzicus to Athens with his students for a short period (Diog. Laert. 8, 87). See note 51, above.

[71] Alexander Zaicev, *Das griechische Wunder: Die Entstehung der griechischen Zivilisation* (Konstanz: Universitätsverlag Konstanz, 1993), pp. 42–47.

[72] On patronage in *mathēmata*, especially in mechanics, see Fraser, *Ptolemaic Alexandria* (cit. n. 60), pp. 305–335; Serafina Cuomo, *Ancient Mathematics* (London: Routledge, 2001), pp. 86, 136–141; and literature listed in note 93, below.

[73] The three periods are 600–325 B.C.E. (from the origin of science to the first great peak), 324–1 B.C.E. (from the first great peak to the end of the big plateau), and 1–550 C.E. (from the beginning of the lesser plateau to the end).

In the first period (see Figure 10) Athens obviously dominated; it was, however, the only polis of mainland Greece that exhibited noticeable scientific activity. The cities of Asia Minor with adjacent islands—this is where science was born—and the Greek colonies of Magna Graecia constitute the other two important regions. The second, most populous, period (see Figure 11) is clearly polycentric: three smaller centers are gone, but seven new ones have appeared, three of which—Alexandria, Rhodes, and Rome—competed with Athens.

In the third period (see Figure 12), dominated by Alexandria, only 9 of the 15 centers remained; all of these except Constantinople were smaller than before, and 5 of them were at the lowest possible level of activity (3 names). This is especially revealing given that the length of the third period was double that of the first. Athens and Miletus are the only specimens, respectively, of a large and a smaller center preserved throughout the entirety of ancient history.

The turning point in the history of ancient science was the crisis of the first century B.C.E., when the number of scientists suddenly dropped, falling by half from 70 to 34 (see Figure 3); the decline was especially rapid after 50 B.C.E. Once stabilized at this level, which was slightly exceeded only once, at 100 C.E., the scientific population stagnated until 500 C.E. Even the final fall of ancient science after 500 C.E. was not as precipitous as that at the end of the Hellenistic period. What, then, are the possible causes for this abrupt decline, contrasting so strongly with the two centuries in which Hellenistic science flourished? Obviously, only a factor external to science, not an inevitable mechanism inherent to it, could so quickly have halved the number of practitioners of mathematics, astronomy, and geography and reduced mechanics to ground level. The same conclusion clearly follows from the simultaneous decline of all the major centers of science of the day—Athens, Alexandria, Rhodes, and Rome. The scientific population of Syracuse, Byzantium, Cyzicus, and Miletus was decreasing as well; Samos and Antioch had fallen earlier and stagnated. There is only one major historical factor that can account for all this: the brutal civil wars in Rome into which the whole Hellenistic world was drawn and which ended in its final subjection to Rome (30 B.C.E.). These wars devastated the

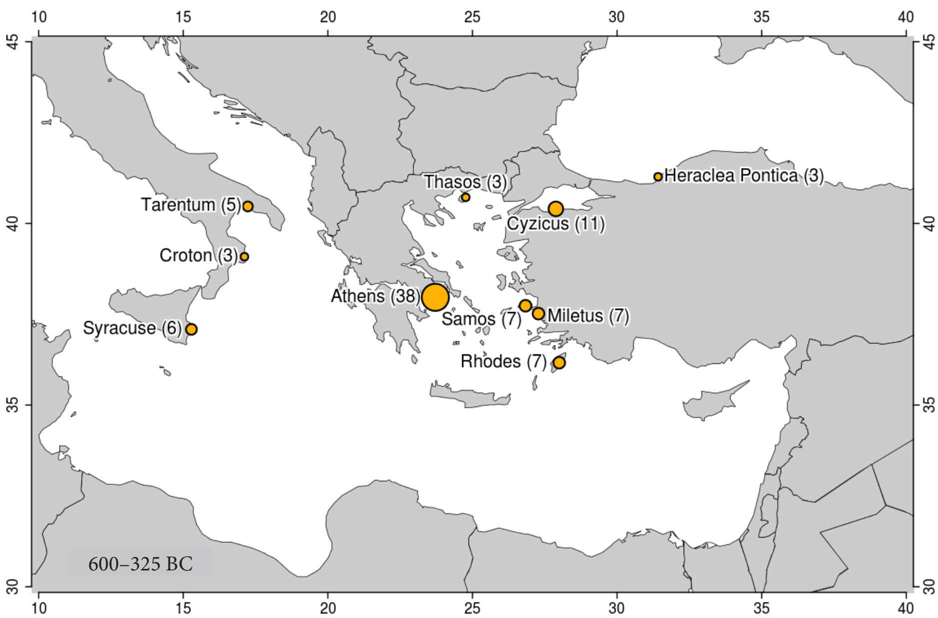

Figure 10. Ancient centers of scientific activity, first period.

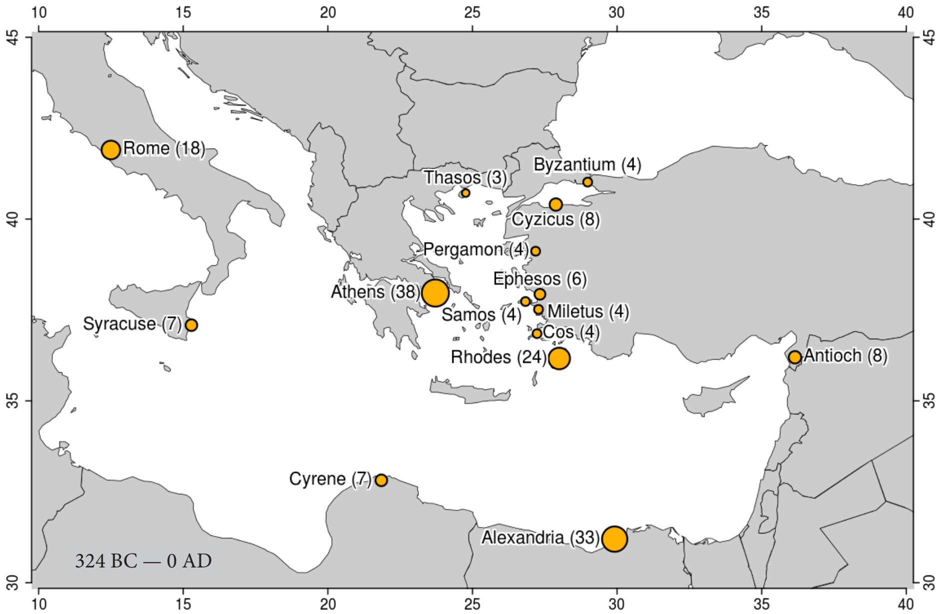

Figure 11. Ancient centers of scientific activity, second period.

Greek world, which experienced a demographic collapse.[74] As centers of scientific activity, Rhodes, Cyzicus, Cyrene, and Syracuse did not recover from this heavy blow, while Athens in the early imperial period remained at one third of its previous level and Alexandria at one half. No event in modern history prior to the two world wars in the twentieth century exerted a comparable influence on the number of scientists.[75]

VII. PLACES OF SCIENCE IN ANCIENT SOCIETY

Though its heyday was over, Greek science turned out to be a sustainable social activity, able to adjust to the realities of the Roman Empire. But what made it sustainable and in what sense was it a social and not merely a cognitive activity? As antiquity did not create organizational structures comparable to those scientists would gradually build and use in the early modern period—universities, academies, scientific societies—the lack of institutional support had to be compensated for by other *social* factors that enabled the rise and continued existence of science. If, however, the scientific role had not yet emerged (Ben-David) and science had no acknowledged place in ancient society (Lloyd),[76] if Greek mathematics was "an enterprise pur-

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[74] Ian Morris, "Economic Growth in Ancient Greece," *J. Institut. Theoret. Econ.*, 2004, *160*:709–742, esp. p. 713.

[75] See Gascoigne, "Historical Demography of the Scientific Community, 1450–1900" (cit. n. 64), p. 555: "The number of scientists at any time was not necessarily affected, at least directly, by major political events (notably wars and invasions) which made an immediate and powerful impact on the country as a whole."

[76] "There was no acknowledged place in ancient thought, or ancient society, for science, or for the scientist, as such. The investigators performed different social roles as doctors or architects or teachers": Geoffrey E. R. Lloyd, *Greek Science after Aristotle* (London: Chatto & Windus, 1973), p. 176. Lloyd discussed the social setting of Greek science in many works. See, e.g., Lloyd, *Magic, Reason, and Experience: Studies in the Origins and Development of Greek Science* (Cambridge: Cambridge Univ. Press, 1979), pp. 226–267; Lloyd, *Methods and Problems in Greek Science* (Cambridge: Cambridge Univ. Press, 1991), pp. 121–140; and Lloyd and Nathan Sivin, *The Way and the Word: Science and Medicine in Early China and Greece* (New Haven, Conn.: Yale Univ. Press, 2002), pp. 82–139. Cf. Dmitri Panchenko, "Social Framework of Early Theoretical Science," in *The Ideals of*

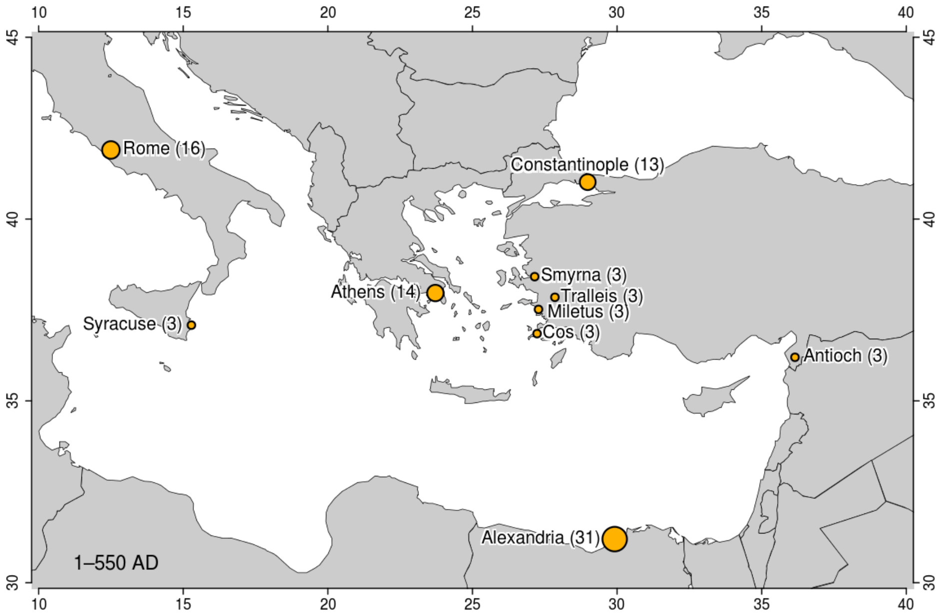

Figure 12. Ancient centers of scientific activity, third period.

sued by *ad hoc* networks of amateurish autodidacts" (Netz),[77] then how did scientific disciplines exist for many hundreds of years and how were scientific norms and values effectively reproduced in each generation? The answer is that both the scientist's role and the place of science in ancient society have to be reconsidered. What we can offer here is necessarily limited to a brief overview of the basic points, with several characteristic examples.

Abundant evidence shows that the core group of those who did (what is by modern standards) scientific work saw themselves and were seen by others as *mathēmatikoi*—that is, as experts in distinct areas of certified knowledge such as geometry, arithmetic, and astronomy that at the end of the classical period were regarded as worthy of their own histories. Since the fourth century B.C.E. *mathēmatikoi* were distinguished from philosophers; during Hellenism the number of philosophers engaged in *mathēmata* or scientists doing philosophy dropped below 10 percent. *Mathēmatikoi* were able to create new and transmit accumulated knowledge by methods generally recognized in their community: deductive proof, calculation, measurement, observation, description, theory building, experiment, and the like. Those who accepted the goals and techniques of science were committed to a voluntarily adopted system of conventions, rules, and norms governing their practice, which allowed them to attain a much greater degree of consensus (even in harmonics, with its two schools) than could be found in philosophy or medicine. Normally scientists shared a conviction that the pursuit of truth in such a way is an end in itself, though many of them envisaged possibilities of practical application of scientific knowledge and some were successful in doing that. Phenomena typical of modern science—such as pretensions to originality, a desire for recognition by peers, criticism and praise of predecessors and contemporaries, priority struggles, and accusations of plagiarism—are amply documented

Joseph Ben-David: The Scientist's Role and Centers of Learning Revisited, ed. Liah Greenfeld (New Brunswick, N.J.: Transaction, 2014), pp. 45–58.

[77] Netz, "Greek Mathematicians" (cit. n. 9), p. 216.

in ancient *mathēmata*. Thus, if the social role is defined as "a pattern of actions, sentiments and beliefs thought by those who perform and experience that pattern and by other persons who perceive it as a distinctive one with a distinctive function of its own and a distinctive appropriateness in particular situations," then the scientist's role as producer of knowledge has emerged in ancient Greece.[78]

When Pythagoras found an incontrovertible proof of his theorem, he was performing a cognitive act, though his desire to make proof incontrovertible was also motivated by his orientation toward his peers, actual or potential. When, wishing to obtain their recognition, he "published" his proof—that is, made it accessible—he performed a social act.[79] By doing this he won wide acclaim, far beyond his fellow mathematicians: his theorem became famous—there was even an epigram about this discovery, quoted by many authors.[80] Thales' "prediction" of a solar eclipse found an early response in Xenophanes and Heraclitus, while Aristophanes used his name as a synonym for "mathematician" and "astronomer." Anaximander's reputation as an astronomer was strong enough that he was invited to Sparta to install a gnomon.[81] All this and much more would have been impossible if engagement in *mathēmata* was not recognized as a socially legitimate, indeed prestigious, activity worthy of pursuit (see the text preceding note 2, above). It is revealing that from the very beginning such activity was sustained by an aristocracy to which Thales, Anaximander, Pythagoras, Hippasus, and (most probably) Democritus belonged. Hippocrates of Chios was a rich merchant, Archytas a political and military leader of Tarentum; Theaetetus's father was a respected citizen of Athens who left him a huge fortune; Eudoxus, though of simple origin, was received on his return to Cnidus with great honor and gave laws to his fellow citizens.[82]

Obviously, ancient Greek society, and first and foremost its literate elites, which overlapped with power elites, not only tolerated free scientific research—that in itself is a very uncommon thing—but also supported it. The principal reason why the Greek polis proved to be a much more favorable environment for scientific studies than most societies before and after it was that Greek society and science shared the same fundamental values and norms. The first was the aspiration to fame and honors, which was among the most important motives for individual behavior on the part of the citizens of the Greek polis and which, as is widely agreed in sociology and psychology of science, constitutes the second basic motive for scientific research in general—after the cognitive quest for truth.[83] More than through any direct institutional or financial support, Greek society unlocked the cognitive potential of the individual by duly rewarding those who proved a geometrical theorem, drew a geographical map, or explained the cause of lunar and solar eclipses with fame and respect.[84]

Another vital feature that ancient science shared with the society that gave birth to it was competitiveness. Lloyd rightly presents competitiveness as the most characteristic feature of

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[78] For the definition see Thomas Schott, "The Movement of Science and of Scientific Knowledge: Joseph Ben-David's Contribution to Its Understanding," Minerva, 1993, *31*:455–477, on pp. 459–460. Cf. Ben-David, *Scientist's Role in Society* (cit. n. 2), pp. 16–17.

[79] See, e.g., Warren Hagstrom, *The Scientific Community* (New York: Basic, 1965), p. 16.

[80] "As when Pythagoras the famous figure found / For which a sacrifice renowned he brought" (*A. P.* 7, 119, trans. Ivor Thomas). See Zhmud, *Pythagoras and the Early Pythagoreans* (cit. n. 11), pp. 267–268.

[81] Anaximander: Diog. Laert. 2, 1. Thales: Eudem. fr. 144; Ar. *Nub.* 177–180, *Av.* 999–1009.

[82] For more detail see Netz, "Greek Mathematicians" (cit. n. 9), pp. 200–201, 215.

[83] As the first historian of the Royal Society noted, "This Desire of Glory, and to be counted Authors, prevails on all": Thomas Sprat, *The History of the Royal Society of London* (London, 1667), pp. 74–75. See, e.g., Noretta Koertge, "A Bouquet of Scientific Values," in *Scientific Values and Civic Virtues*, ed. Koertge (Oxford: Oxford Univ. Press, 2005), pp. 9–24.

[84] Zaicev, *Das griechische Wunder* (cit. n. 71), pp. 121–143.

Greek science and, more widely, of Greek intellectual life,[85] yet to evaluate it properly we should consider its social roots. The early Greek polis was a highly competitive society; the orientation toward success, toward surpassing others in the achievement of one's life goals, played a tremendous role even in those cases where a victory brought little in the way of practical benefits—for example, in athletic games. This agonistic spirit, emphasized by Jacob Burckhardt, contributed to establishing a new value orientation toward priority *as such*, independent of whether the victor himself or his polis benefited from it materially. Creative achievements of all sorts were stimulated, irrespective of their practical utility.[86]

Indeed, Greek science, unlike the mathematics and astronomy of ancient Egypt and Mesopotamia, originated as a mostly nonutilitarian enterprise, not least owing to the powerful antiutilitarian ethos of aristocratic Greek society. An attitude that held knowledge to be a value in itself—still strong, though in a modified form, among those who do basic research—contributed greatly to the rise of Greek science, especially in the early period, when it could offer knowledge that was useful for society only sporadically. This view has been best expressed by Plato and Aristotle, who emphatically preferred the nonutilitarian value of *mathēmata* to their usefulness. We have to bear in mind, however, that they themselves reacted to a competing attitude that can be called "normal" for a society: "He who knows useful things, not many things, is wise."[87] Both Plato's teacher Socrates and his rival Isocrates shared the common-sense attitude toward *mathēmata*, typical also of the Sophists.[88] Most men, says Isocrates, see in *mathēmata* such as geometry and astronomy nothing but empty talk and hair-splitting (*Antid.* 262). But some praise the utility of these sciences, while others attempt to demonstrate that they are conducive in the highest measure to the attainment of virtue (*Bus.* 23). What Isocrates articulated here was the position of the *mathēmatikoi*: Archytas, for example, has argued that arithmetic (calculation) contributed greatly to both an increase of social concord and equality and an improvement of man's moral qualities (47 B 3 DK).

Thus, for those working in *mathēmata* or theorizing about them in the ancient world the same basic paths and attitudes were open as in the modern: they could believe and argue that science is valuable *per se* and that it is useful for life. This greatly enhanced the adaptiveness of science to the needs and values of society and allowed scientists to be proud of their practically oriented discoveries. When the mid-fifth-century B.C.E. astronomer and geometer Oenopides of Chios found an intercalation fifty-nine-year cycle for the lunisolar calendar, he dedicated a bronze tablet describing his discovery at Olympia—a place where people from the whole Greek world came to compete for fame. When the Athenian astronomer Meton introduced a more precise nineteen-year cycle in 432 B.C.E., he found a no less significant place to erect a stele with an inscription and/or an astronomical instrument, *heliotropion* (the sources suggest both possibilities): the wall of Pnyx behind which Athenian ecclesia assembled.[89] Eratosthenes was so proud of having invented a new device for doubling the cube that he dedicated a bronze model of it to King Ptolemy III, adding a fine epigram that emphasized the device's practical utility.[90] Archimedes' biographer Heraclides pointed out that his book *On Measuring the Circle*

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[85] See the works by Lloyd cited in note 76, above.

[86] Jacob Burckhardt, *The Greeks and Greek Civilization*, ed. Oswyn Murray (New York: St. Martin's Griffin, 1998); and Zaicev, *Das griechische Wunder* (cit. n. 71), pp. 121–143.

[87] Aeschylus fr. 390 N^2.

[88] Socrates: Xen. *Mem.* IV, 7.1–8. Isocrates: *Antid.* 261–266; and *Panath.* 26–29. See Zhmud, *Origin of the History of Science in Classical Antiquity* (cit. n. 15), pp. 71–76.

[89] Oenopides: Ael. *VH* 10, 7 = 41 A 9 DK; Meton: Ael. *VH* 10, 7; and Diod. Sic. 12, 36, 3.

[90] Eutoc. *In Archim. De sphaer.*, 88.3–96.9. Philo of Byzantium used the duplication of the cube in his treatise on artillery, Diocles in *On Burning Mirrors*; see Cuomo, *Ancient Mathematics* (cit. n. 72), pp. 83–88.

is useful for the necessities of life.[91] Generally, from the third century B.C.E. forward "practical utility" (*tas en tō biō chreias*), though variously understood, is a recurrent topic in introductions to mathematical and mechanical treatises in various genres.[92]

In the Hellenistic period Greek science found ever new places for itself in society. The main channels of the "socialization" of *mathēmata* during this period were mechanics—especially where related to war machines and water-lifting devices, but also to entertainment—and astronomy dealing with calendars and timekeeping. In the second–first centuries B.C.E. sundial development reached its peak "in terms of both the number of kinds produced as well as their quality."[93] First attempts at popularizing scientific knowledge were made in the third century B.C.E. Aratus's poetic adaptation of Eudoxus's *Phaenomena*, commissioned by King Antigonus Gonatas, brought him extraordinary success: five Greek biographies, a dozen commentaries on his learned poem, and at least four Latin translations. Archimedes addressed his popular treatise *The Sand Reckoner* to King Gelon. The achievements of Hellenistic scientists, raising awareness of science among the educated classes and sparking a renewed interest in *mathēmata* on the part of the major philosophical schools, secured a new place for science in society: from the first century B.C.E. the mathematical quadrivium grew to become a part of the educational curriculum (*enkyklios paideia*).[94] The quadrivium was taught until the very end of antiquity and was later taken up by the Arabs, who translated the principal works of Greek *mathēmatikoi*; these works in turn were translated into Latin from the tenth and especially the twelfth century.[95] From this time on science has had an ineradicable place in society.

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[91] Eutoc. *In Apollon. con.*, 168.5f.

[92] Mansfeld, *Prolegomena Mathematica* (cit. n. 34), index s.v. "isagogical questions: utility."

[93] Karlheinz Schaldach, "Measuring the Hours: Sundials, Water Clocks, and Portable Sundials," in *Time and Cosmos in Greco-Roman Antiquity*, ed. Alexander Jones (Princeton, N.J.: Princeton Univ. Press, 2016), pp. 63–93, on p. 71. On mechanics see, e.g., John Peter Oleson, *Greek and Roman Mechanical Water-Lifting Devices* (Toronto: Univ. Toronto Press, 1984); Astrid Schürmann, *Griechische Mechanik und antike Gesellschaft* (Stuttgart: Steiner, 1991); Serafina Cuomo, *Technology and Culture in Greek and Roman Antiquity* (Cambridge: Cambridge Univ. Press, 2007), pp. 62–67; and Berryman, *Mechanical Hypothesis in Ancient Greek Natural Philosophy* (cit. n. 44), pp. 154–176.

[94] See above, notes 27, 30. In the same century four *mathēmata* entered the Roman encyclopedic and didactic tradition that lasted from Varro's *Disciplinarum libri IX* up to Augustine, Martianus Capella, and Boethius and made its way into the early Middle Ages.

[95] Gerhard Endress, "Mathematics and Philosophy in Medieval Islam," in *The Enterprise of Science in Islam: New Perspectives*, ed. J. P. Hogendijk and A. I. Sabra (Cambridge, Mass.: MIT Press, 2003), pp. 121–176; Dimitri Gutas, "Geometry and the Rebirth of Philosophy in Arabic with al-Kindī," in *Words, Text, and Concepts Cruising the Mediterranean Sea*, ed. R. Arnzen and J. Thielmann (Leuven: Peeters, 2004), pp. 195–209; and Ahmad Y. al-Hassan, "Transmission of Islamic Science to the West," in *The Different Aspects of Islamic Culture*, Vol. 4, ed. al-Hassan (Paris: UNESCO, 2001), pp. 133–166.