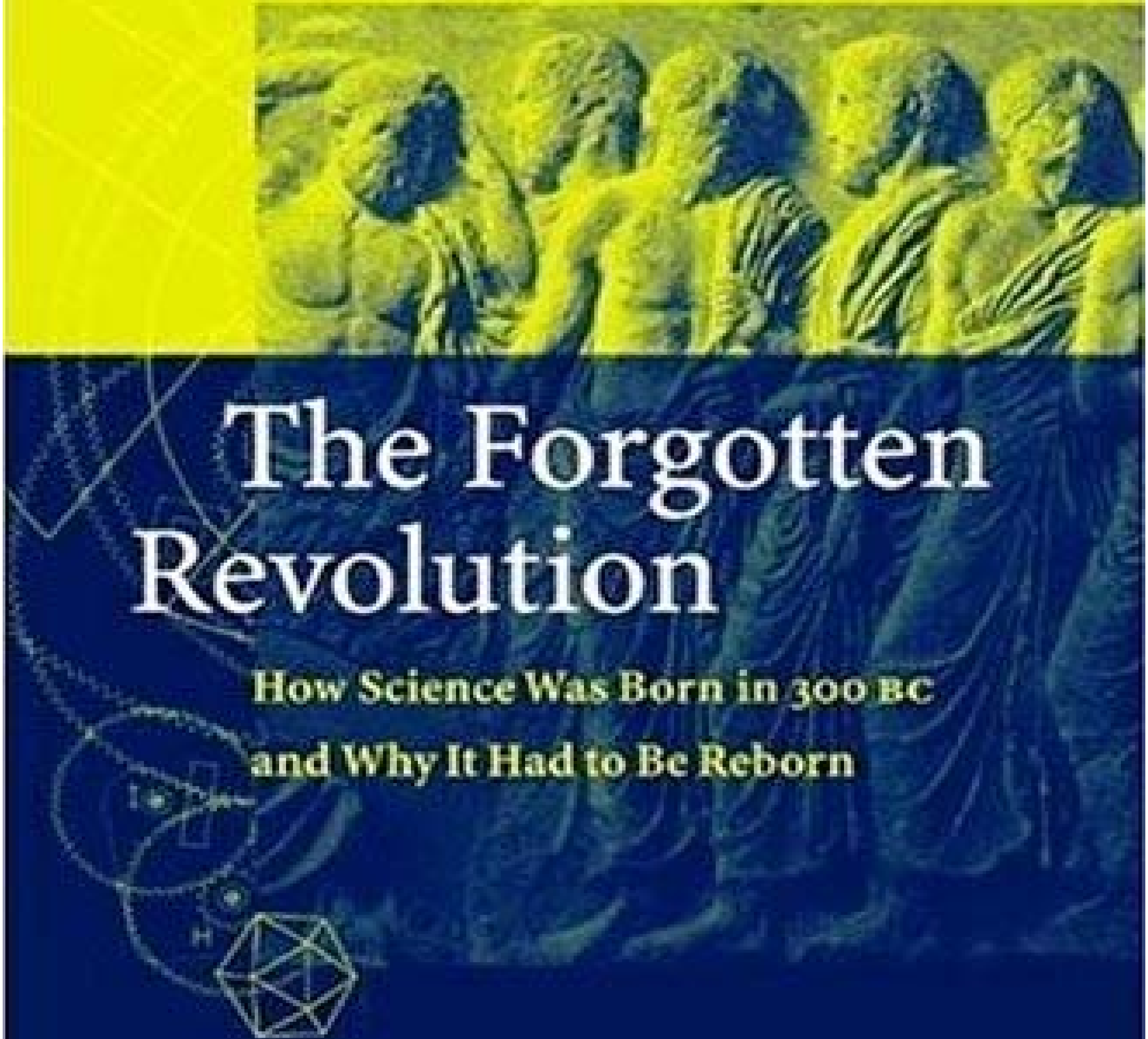
Lucio Russo



The Forgotten Revolution

How Science Was Born in 300 BC and Why It Had to Be Reborn

Springer

Contents

Introduction

The period from the late fourth to the late second century B.C. witnessed, in Greek-speaking countries, an explosion of objective knowledge about the external world. While Greek culture had reached great heights in art, literature and philosophy already in the earlier classical era, it is in the so-called Hellenistic period that we see for the first time — anywhere in the world — the appearance of science as we understand it now: not an accumulation of facts or philosophically based speculations, but an organized effort to model nature and apply such models, or *scientific theories* in a sense we will make precise, to the solution of practical problems and to a growing understanding of nature. We owe this new approach to scientists such as Archimedes, Euclid, Eratosthenes and many others less familiar today but no less remarkable.

Yet, not long after this golden period, much of this extraordinary development had been reversed. Rome borrowed what it was capable of from the Greeks and kept it for a little while yet, but created very little science of its own. Europe was soon smothered in the obscurantism and stasis that blocked most avenues of intellectual development for a thousand years — until, as is well known, the rediscovery of ancient culture in its fullness paved the way to the modern age.

What were the landmarks in the meteoric rise of science 2300 years ago? Why are they so little known today, even among scientists, classicists and historians? How to they relate to the post-1500 science that we're familiar with from school? What led to the end of ancient science? These are the questions that this book discusses, in the belief that the answers bear on choices we face today.

This is so for several reasons. A better understanding of ancient science and how it relates to its modern counterpart can shed light on the internal structure of science, on its links to technology and other aspects of modern civilization, and on the origins of, and possible remedies for, the contemporary rift between the humanistic and scientific worlds. But what makes ancient science an even more relevant topic, and at the same time helps explain the low esteem in which it has been held in the last two centuries, is its tragic end. The naïve idea that progress is a one-way flow automatically powered by scientific development could never have taken hold, as it did during the 1800s, if the ancient defeat of science had not been forgotten. Today such dangerous illusions no longer prevail absolutely, and we may have a chance to learn from the lessons of the past. Those who engage in defending scientific rationality against the waves that buffet it from many directions would do well to be forearmed with the awareness that this is a battle that was lost once, with consequences that affected every aspect of civilization for a thousand years and more.

Another reason to delve into Hellenistic science is historical. As we shall argue, the rise of the scientific method was part of a more general trend: roughly speaking, in Hellenistic times the creation of culture became a conscious act. Not only do we see physicians conducting controlled experiments, scientists using mathematics and mechanics to build better weapons, painters applying geometry to their art, but even the notion of language changes: poetry becomes a playground for experimentation, while words are consciously assigned precise new meanings in technical fields, a procedure that would not become familiar again until the nineteenth century. The material component of prescientific societies is largely defined by their technology; but once technology starts to be consciously developed through science, the two become inseparable, and science takes on a vital role, down to the very way a society sees itself.

In sum, an appreciation of the original *scientific revolution* is essential for the understanding of Hellenistic civilization; in turn, the role it played in that civilization can help us better analyze key historical questions, such as Rome's legacy, the causes of urban and technological decline in the Middle Ages, and the origins, features and limitations of what is called the early modern *scientific renaissance*. In this sense the subject of this book is not so much History of Science as simply History — "history via science", so to speak, just as one may study history through the "material civilization", or through literature, or, more traditionally, though a political and military lens. In the case of the Hellenistic period and its aftermath, the approach via science and technology seems to me particularly fruitful.

Reader's Advisory

The reader who peruses the Table of Contents will notice that the book weaves together many threads, offering general formulations but also a wealth of examples. That the subject matter overlaps with so many distinct specialties means there is no hope of giving a complete picture of the literature. Therefore the bibliography's 340 works fall roughly into two types: on the one hand, many of the articles and books of twentieth- and nineteenth-century scholarship I have drawn on, and which I feel are most important or helpful — sometimes as an entry point to the bibliography on a specific subject. On the other hand, the goal of some citations and references is to illustrate a widespread opinion; in those cases the choice is not necessarily of the best works, but of the most popular and therefore most representative. Several of these are encyclopedic works.

Citations of works in the bibliography are given in brackets, together with page numbers (sometimes for multiple editions; or else an edition-invariant method of location may be used instead).

The 200 or so ancient texts referred to, plus another hundred medieval and early modern works, are collected in a separate List of Passages, where the reader unfamiliar with the conventions of classicists may turn for additional help. Both in that list and in the text, the references are as explicit as possible, often including both the chapter/section number and (as the first not otherwise marked arabic numeral) the page number in the reference edition. Although "Plato, *Republic*, VI, 510c" will easily be found in any edition or translation, since they all correlate with the reference edition (Henri Estienne, Geneva, 1578), the situation for many other texts is not so neatly standardized. In such cases, at the cost of perhaps being thought too fussy, I have felt it better to spell out the edition to which the page numbers refer, or to offer in other ways what to a specialist might be redundant information.

All chapters and sections are interconnected, and not as independent as their titles might suggest. The reader who chooses to dip into the text here and there will be in turn informed, challenged to reflection, occasionally amused or amazed, perhaps infuriated; but for the full benefit of logical argumentation, the book is best read sequentially. Nevertheless, a comprehensive subject index and a network of cross-references will help those who are primarily interested in a particular topic.

Acknowledgments

I would probably not have been able to bring this work to fruition had it not been for the support of two great classicists: Carlo Gallavotti, who many years ago read my first articles on Hellenistic science and who, with his feedback, extended to me crucial words of encouragement; and Bruno Gentili, in whom I found a valuable ally in subsequent years.

As the theses contained in this book were maturing, I had the chance to teach several times a course on the History of Mathematics. My work owes much to the enthusiasm and intelligence with which many of my students embraced the study of questions raised in the course, grasping their importance and topicality in defiance of current fads.

I thank Marcello Cini for his attentive reading of the original manuscript, for bringing it to the attention of the Italian publisher Feltrinelli, and for his comments.

I am indebted to many friends and colleagues who gave me feedback, suggestions and criticism to early versions of these pages or the articles where some of the material first appeared. They all taught me something, but I wish to extend my warmest thanks to Donatella Capocaccia, Giovanni Ciccotti, Ferdinando Degan, Henri Epstein, Giorgio Fusco, Giovanni Gallavotti, Alberto Gandolfi, Sandro Graffi, Mario Iannuzzi, Giovanni Jona-Lasinio, Marco Lippi, Gabriele Lolli, Enzo Olivieri, Luigi Radicati, Archie Roy and Giovanni Stelli.

In preparing the second Italian edition I tried to take into account the many comments I got from reviewers, colleagues, friends and students. I thank them all, but especially Fabio Acerbi, Riccardo Caneba, Giovanni Cerri, Filippo Franciosi, Emanuele Narducci and Paolo Radiciotti.

1
The Birth of Science

1.1 The Erasure of the Scientific Revolution

Given the central and widely recognized role science plays in our civilization, one might think that the birth of science would be regarded as a crucial juncture in human history. Instead, its importance is almost never perceived. Histories of scientific thought tend to obscure the revolutionary state of knowledge in the age of Archimedes — the Hellenistic period — toning down the differences between it, the natural philosophy of classical Greece two centuries earlier, and even the prescientific knowledge of ancient Egypt and Mesopotamia. The omission is even more glaring in histories of Antiquity: one can typically find more information about Archimedes or Aristarchus of Samos in a book about the Renaissance, in connection with their rediscovery, than in a work on classical civilization.

A person who studies the modern age thinks of the Renaissance or the seventeenth century with eyes set on the future, toward contemporary civilization. She therefore cannot ignore the importance of the "rebirth of science". The student of Antiquity, on the contrary, often has (and in the past even more so) the tendency to contrast the Hellenistic period either with the supposed perfection of classical Greece or with Rome. He thus runs the risk of judging it either by the standards of an earlier civilization or by those of a civilization to which science remained foreign; in either case, from the point of view of a prescientific culture.

The result is that most authors were led to identify the birth of scientific method with what, not by accident, is called the Scientific Renaissance, and that until the nineteenth century the civilization that gave us science

was not even considered worthy of a name: it was just a "period of decadence" of Greek civilization.

Droysen was the first historian to reevaluate this extraordinary period and give it a name, in his *Geschichte des Hellenismus*.[1]

In the last half-century things have become clearer; today one can find very interesting works on various aspects of Hellenistic civilization.[2] But in general these are specialized works that have not changed much the general picture available to the educated public, to whom the Hellenistic period often continues to appear as one whose cultural heritage is for us less essential than that of the classical period.

There seems to have been in fact an erasure of Hellenistic civilization, and in particular of the scientific revolution that took place in the third century B.C., from our collective historical conscience, not unlike the phenomenon of repressed memories. Our culture, though built on the twin foundations of history and science, resorts to various expedients to hide from itself the historical importance of the birth of science.

Let's consider three great beacons of the scientific revolution: Euclid of Alexandria, Archimedes of Syracuse, Herophilus of Chalcedon. What does an educated person know about them?

About Herophilus, nothing.[3] About Archimedes one remembers that he did strange things: he ran around naked shouting *Heureka!*, plunged crowns in water, drew geometric figures as he was about to be killed, and so on. The childish store of anecdotes associated with his person and the meager diffusion of his works give the impression that Archimedes has more in common with figures of myth and legend than with other thinkers. So he is remembered, yes, but as a legendary character, outside of history. One ends up forgetting that he was a scientist of whom we still have many writings and whose results continue to be part of scientific education at many levels — from the formula for the volume of a sphere, learned in elementary school, to university-level notions of mechanics and mathematical analysis that were born with his work.

Euclidean geometry has remained throughout the centuries the framework for basic mathematical teaching.[4] But Euclid himself has been taken out of history. In his case the mechanism is opposite the one used for

[1][Droysen].

[2]Some of them will be cited later. Among the works of broad scope on the Hellenistic age I still consider [Rostovtzeff: SEHHW] fundamental, while [Green] is a good representative of more recent tendencies. Regarding Alexandria, in particular, much information and above all a useful collection of testimonies can be found in [Fraser].

[3]We will return to him in Chapter 5.

[4]In view of the failure of attempts to base teaching on axiomatic systems devoid of geometric content, the tendency today is increasingly not to teach the deductive method in high school at all; but I do not think that such teaching can be fairly classified as mathematical.

Archimedes: instead of being depicted in legend and in anecdotes, he is offered to us without any historical context, laying down "Euclidean geometry" as if it were something that had always been there at mankind's disposal. If you are not convinced of this, try asking your friends what century Euclid lived in. Very few will answer correctly, in spite of having studied Euclidean geometry for several years.[5] And yet Euclid has been one of the most read authors in the history of humanity; his most famous work, the *Elements*, has been studied without interruption for twenty-two hundred years: from 300 B.C. to the end of the nineteenth century. There is probably no author as well-studied (though not at first hand nowadays) about whom we know so little in general.

Another mechanism leading to the erasure of Hellenistic civilization, and particularly of the century of greatest scientific development, the third century B.C., is the vague attribution of results, especially scientific or technological, to "the Ancients". For example: one always says that the diameter of the Earth was measured "in Antiquity", that "the Ancients" discovered the principle of hydrostatic pressure, that the organ goes back "to Antiquity", that Copernicus had a precursor "in Antiquity". We will see many other examples later.

The difficulty one experiences in trying to frame historically the facts and individuals of the third century B.C. is tied to our profound ignorance of that period, which has been almost obliterated from history.

First of all, there remains no sustained historical account of the period between 301 (when the *Bibliotheca historica* of Diodorus Siculus breaks off[6]) and 221 B.C. (the beginning of Polybius's *Histories*, which also reached us incomplete). Not only do we have no historical works dating from the Hellenistic period, but even the subsequent work of Livy is missing its second ten books, which contained the period from 292 to 219 B.C. The tradition preserved the history of classical Greece and that of the rise of Rome — the periods that remained cultural reference points in the late Empire and in the Middle Ages, whereas the history of the century of scientific revolution was forgotten with the return of civilization to a prescientific stage.

Secondly, almost all writings of the time have been lost. The civilization that handed down to us, among so many intellectual achievements, the very idea of libraries and of the zealous preservation of the thinking of the past, was erased together with its works. We have a few scientific works transmitted through Byzantium and the Arabs, but Europe preserved none. A little has been recovered: a few papyrus fragments

[5]This at least is the result of a little personal survey conducted among my friends and colleagues.

[6]At the end of Book XX; of later books we have only fragments.

found in Herculaneum[7] comprise all we can read of the hundred or so books written by Chrysippus, who was according to many testimonies the greatest thinker of his time; a fundamental work, Archimedes' *The method*, was fortuitously discovered in 1906 by Heiberg (on the famous palimpsest subsequently lost and found again in 1998); and thanks to recent papyrus finds we can read Menander. But these favorable cases are few.

The seriousness of the destruction of Hellenistic works has usually been underestimated in the past, due to an assumption that it was the best material that survived. Unfortunately, the optimistic view that "classical civilization" handed down certain fundamental works that managed to include the knowledge contained in the lost writings has proved groundless. In fact, in the face of a general regression in the level of civilization, it's never the best works that will be saved through an automatic process of natural selection. That the same tradition that preserved in their totality the 37 books of Pliny's *Natural history* overlooked the few pages of Archimedes' seminal treatise *The method* is in itself a proof that the tendency is exactly the opposite. Late Antiquity and the Middle Ages favored compilations, or at least books written in a language still understandable to a civilization that had returned to the prescientific stage. Thus we have Varro's work on agriculture and Vitruvius' on architecture, but not their Hellenistic sources; we have Lucretius' splendid poem on nature, but not the works of Strato of Lampsacus, who according to some indications may have originated natural science in the true sense. Even among real scientific works, some of which were preserved by the Byzantines and Arabs, two selection criteria seem to have been at work. The first was to give preference to authors of the imperial period, whose writings are in general methodologically inferior but easier to use: we have, for example, Heron's work on mirrors, but not the treatise that, according to some testimonies, Archimedes wrote on the same subject. Next, among the works of an author the ones selected are generally the more accessible, and of these often only the initial portions. We have the Greek text of the first four, more elementary, books of Apollonius' *Conics*, but not the next four (of which three survived in Arabic); we have Latin and Arabic translations of the work of Philo of Byzantium on experiments in pneumatics, but none of his works on theoretical principles. We will see further examples of these selection criteria.

A third reason for our ignorance is that until recently there had been no systematic excavation of the centers of Ptolemaic Egypt. Even in the

[7]Herculaneum and Pompeii had an intense interchange with the Hellenistic world until their sudden destruction in 79 A.D. The Vesuvius eruption thus had the effect of saving precious testimonies of Hellenistic art and culture from the loss that took place elsewhere in the late Empire and early Middle Ages.

case of Alexandria, the submerged remains of the ancient city only began to be explored systematically in 1995. Much of our knowledge of Ptolemaic Egypt comes form papyri found in the last hundred years. These are fortuitous finds, in general discarded sheets used as "waste paper" by embalmers.

Fourthly and finally, apart from some diplomatic and military events that come to our ken through the Roman pen and from the paltry legal data and the like that we glean from inscriptions, our knowledge about Hellenistic states other than Egypt is virtually nil. Our lack of information about the Seleucid kingdom, which included Mesopotamia, is particularly jarring, because there are several indications that its contribution to scientific development may have been comparable to Ptolemaic Egypt's. Our ignorance derives only in part from the perishability of parchment and papyrus, which will not last for millennia except under exceptional climates such at that of certain areas of Egypt. Hellenistic Mesopotamia still used cuneiform writing on clay tablets, a much more durable material; but this fortunate circumstance does not appear to have been exploited to any great extent. The historian Rostovtzeff writes:

> We know rather more of Babylonia than of the other eastern parts of the empire. A few Greek inscriptions, the ruins of some buildings of Hellenistic date and, most important of all, thousands of cuneiform tablets of the same period mostly from Babylon and Uruk have been found. Very few of these have been read and published and even fewer translated...[8]

Perhaps what we have called "erasure" is a phenomenon profoundly characteristic of our culture. Not only are cuneiform tablets not being read, but even the Hellenistic writings that have come down to us in Greek are often not found in accessible editions.[9]

We will try to identify the origins of this erasure in this book. And if on the one hand the scarcity of sources makes it hard to prove any thesis whatsoever, on the other hand one should not be astounded if some of the current and earlier interpretations turn out to be misguided. If we face Hellenistic scientific culture without doing our best to forget it, we may encounter surprises and be forced to modify many longstanding ideas about "Antiquity".

[8] [Rostovtzeff: SE], p. 187.

[9] For example, there is no critical edition of the fragments of Eratosthenes. The only attempt in that direction, by G. Bernhardy, dates from 1822. For scientific works there is no collection of classics comparable to the various existing authoritative series devoted to literary or philosophical works.

1.2 On the Word "Hellenistic"

To give a sense to the claim that science was born during the Hellenistic age, it is well to agree beforehand about the meaning of "Hellenistic" and of "science". This section and the next define these two terms.

We start by locating in time and space the civilization that concerns us and some of the protagonists of the scientific revolution. The Hellenistic age, in the terminology introduced by Droysen and accepted by later historians, starts in 323 B.C., with the death of Alexander the Great.[10] His empire broke apart after that, giving rise to several political entities, which were at first governed in the name of the emperor by various pretenders to that title and later became autonomous kingdoms. The three main states were:

- Egypt, with the new city of Alexandria (founded by Alexander in 331 B.C.) as its capital, and ruled by the Ptolemaic dynasty, which also governed Cyprus, Cyrenaica, and in the third century B.C. Phoenicia and Palestine;
- the Seleucid state, with Antioch as its capital, comprising Syria, almost all of Asia Minor, Mesopotamia, Persia, and after 200 B.C. also Phoenicia and Palestine;
- the Antigonid state, comprising Macedonia and some cities in Greece.

There were also smaller states, such as the kingdom of Pergamum, ruled by the Attalid dynasty, the Pontus, and Bithynia. One Hellenistic state of which we know little, but which probably had a major role as a channel between Hellenistic culture and Indian and Chinese cultures was Bactria, which overlapped with today's Afghanistan, Uzbekistan, and Tajikistan.

Hellenistic civilization was not solely the product of Greeks who dwelt in regions that had formed Alexander's empire; it also enjoyed the contributions of autonomous Greek cities, which were spread all over the Mediterranean. Among the important autonomous centers were Rhodes, Syracuse and Massalia (Marseilles).

Hellenistic science boomed in the third century B.C. and has often been called Alexandrian because it had its main center in Alexandria, in Egypt. Among the reasons for this supremacy were the policies of its early rulers, particularly Ptolemy I Soter, who was in power from 323 to 283 B.C., and Ptolemy II Philadelphus, who ruled from 283 to 246.

[10] It might seem more logical to make the Hellenistic period start with Alexander's expedition or his reign, given that its essential new element was the fulfilment of Alexander's program of Hellenization of the territory of the ancient empires. The difference of a few years matters little, of course, but the (slightly morbid) choice of a starting point suggests that even Droysen shared to some extent the prejudice about "Hellenistic decadence".

It was in Alexandria that Euclid worked and taught, around the end of the fourth century B.C.. Also there, in the first half of the next century, lived Ctesibius, creator of pneumatics and founder of the Alexandrian school of mechanics, and Herophilus of Chalcedon, founder of scientific anatomy and physiology.[11] The activity of Aristarchus of Samos, famous above all for having introduced heliocentrism, dates from the same period.[12] It was also most likely in Alexandria that Archimedes (287–212) studied, and even while in Syracuse he remained in constant communication with Alexandrian scientists. Among the scientists of the second half of the third century was Eratosthenes, head of the Library at Alexandria, who, among other things, carried out the first true measurement of the size of the Earth. Chrysippus, who will interest us in particular for his contributions to logic, lived during the same century in Athens, which continued to be the main center for philosophical studies. The activities of Philo of Byzantium, who continued the work of Ctesibius, probably date from the second half of the century. At the turn of the next century there was the work of Apollonius of Perga, to whom we owe in particular the development of the theory of conic sections.[13] The greatest scientist of the second century B.C. was Hipparchus of Nicaea, who was active in Rhodes and studied mainly astronomy.

Starting with the year 212 B.C., which witnessed the plunder of Syracuse and the killing of Archimedes, Hellenistic centers were defeated and conquered by the Romans. During the second century B.C. scientific studies declined rapidly. Alexandria's scientific activity, in particular, stopped abrutly in 145–144 B.C., when Ptolemy VIII (Euergetes II), who had just ascended the throne, initiated a policy of brutal persecution against the city's Greek ruling class. Polybius says that the Greek population of Alexandria was almost entirely destroyed at that time;[14] Athenaeus gives a lively description of the subsequent diaspora of the city's intellectuals;[15] other sources give a few more details.[16] Our information is not enough to reconstruct the causes of the persecution. Subsequently, Euergetes II

[11]It is certain that Ctesibius was active during the reign of Ptolemy II Philadelphus; see, for example, [Fraser], vol. II, p. 622. We will come back to the problem of dating Herophilus.

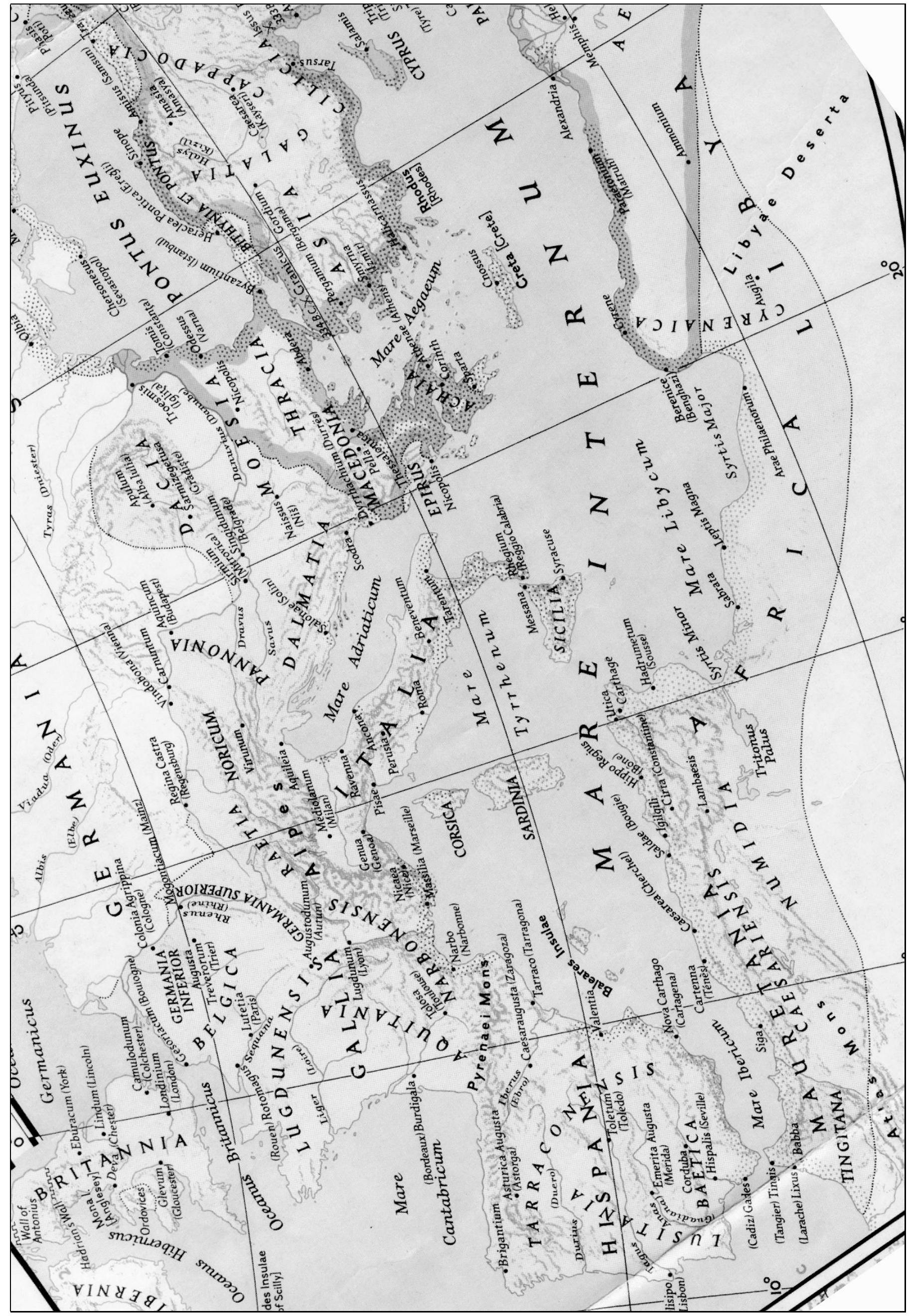
[12]Ptolemy tells us that οἱ περὶ ᾿Αρίσταρχον (“Aristarchus's collaborators” or “the school of Aristarchus”) made an observation in 279 B.C. (*Almagest*, III, i, 206, ed. Heiberg, vol. I.1). We also know from Aetius (in Stobaeus, *Eclogae* I, xvi §1, 149:6–7 (ed. Wachsmuth) = [DG], 313b:16–17) that Aristarchus had been a disciple of Strato of Lampsacus, who headed the Peripatetic school until 269 B.C.

[13]For the dating of Apollonius see G. J. Toomer, *Apollonius of Perga*, in [DSB], vol. I, 179–193.

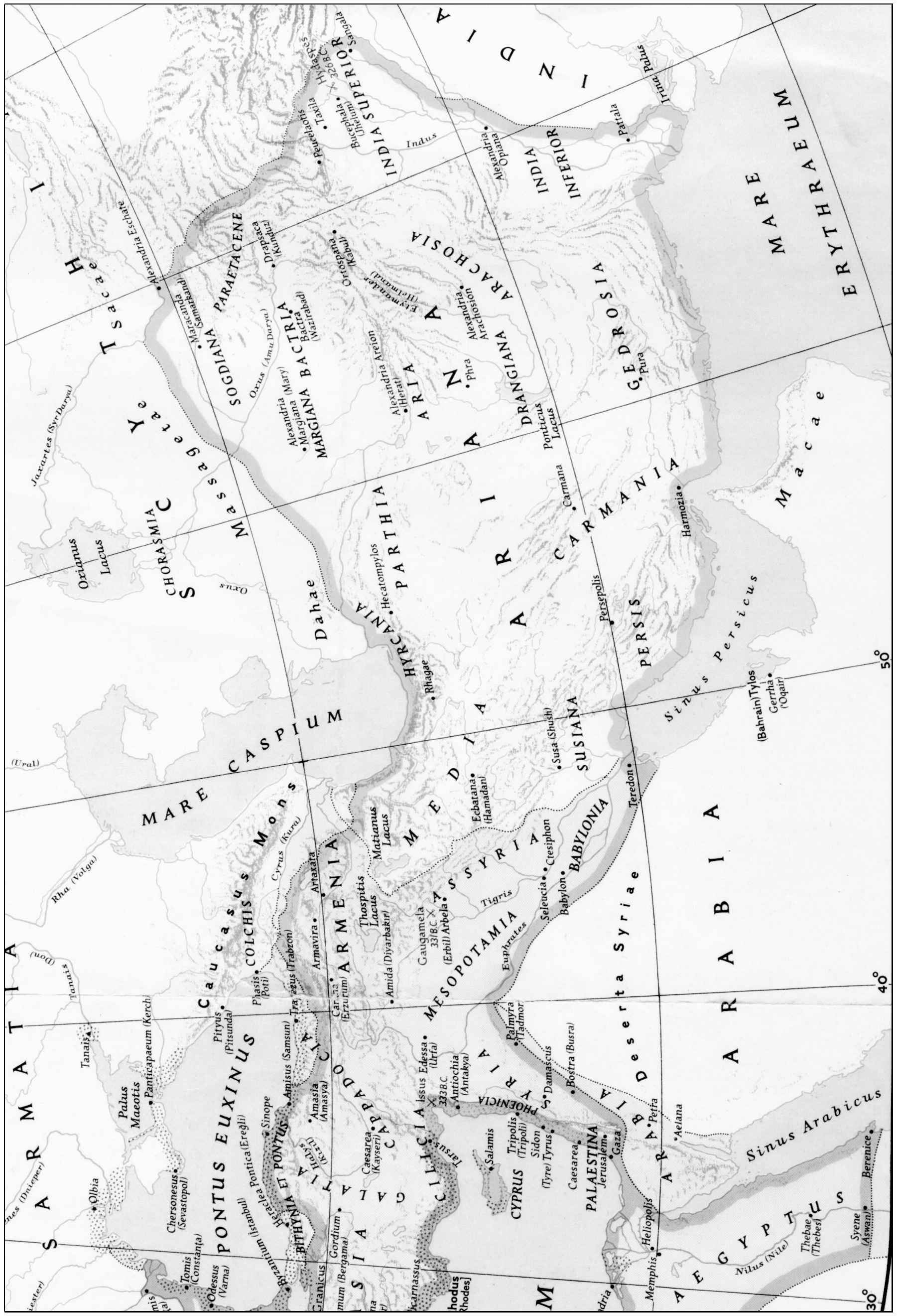
[14]Polybius, *Historiae*, XXXIV, xiv = Strabo, *Geography*, XIV, xx §19.

[15]Athenaeus, *Deipnosophistae*, IV, 184b–c.

[16]For instance, Valerius Maximus tells us that the king ordered the gymnasium surrounded and all those within killed (*Factorum et dictorum memorabilium libri IX*, IX, ii, ext. 5). The few other sources we have on the persecution are collected in [Fraser], vol. II, pp. 216 ff.



For both maps: Gray strip indicates boundary of Alexander's empire in 325 B.C. Darker land indicates Roman empire in 116 A.D. Dots near the coast indicate



Greek and/or Punic settlements. Adapted from the *National Geographic Magazine*, December 1949. Used with permission of the National Geographic Society.

continued to pursue a policy hostile to the Greek community in Alexandria, turning to the indigenous ethnic groups for support.[17] Since he had enjoyed Roman support even before ascending the throne (when, exiled by his brother, he had taken refuge in Rome[18]), it is reasonable to think that he became a proxy for Rome’s Mediterranean expansionism,[19] which at the time was particularly violent.[20]

Rome’s expansion ended in 30 B.C. with the annexation of Egypt, thus completing the unification of the whole Mediterranean under Roman rule. This event is usually considered as the end of the Hellenistic era, which was followed by the “imperial period”. From our point of view, however, it is not a particularly significant date: although the golden age of science had tragically come to an end over a century earlier, with the end of scientific activity in Alexandria and the conquest of the other main centers by the Romans, Hellenistic culture survived during the imperial age. The former kingdoms, in fact, were not assimilated linguistically or culturally, and from the technological and economic point of view there was perhaps more continuity with the preceding period than similarities with the Latin-speaking West. For this reason one sometimes continues to use the term Hellenistic to refer to the culture of the part of the Roman Empire where Greek remained the dominant language.

After the interruption caused by the wars with Rome, the Pax Romana allowed a partial resumption of scientific research in the first and second centuries A.D. — the time of Heron, Ptolemy and Galen — after which the decline was unstoppable. For another couple of centuries, Alexandria remained the center of what scientific activity there was. The last scientist worthy of note may have been Diophantus, if, as has often been thought, he lived in the third century A.D.[21]

The activity documented in the fourth century A.D. is limited to compilations, commentaries and rehashings of older works; among the commentators and editors of that time we will be particularly interested in Pappus, whose *Collection* brings together many mathematical results that

---

[17] The Alexandrians managed to chase him away, but he reconquered the city in 127 B.C.

[18] Polybius, *Historiae*, XXXI, xx.

[19] This impression appears to be confirmed by an inscription in Delos, which contains the dedication of a statue to a general of Euergetes II, on the part of the Roman merchants, in acknowledgement *of the privileges granted them when Alexandria was taken by the king Ptolemy Euergetes* (that is, Euergetes II). The dedication does not refer to the events of 145–144, but to those of 127. The inscription ([OGIS], 135) is reported in [Fraser], vol. II, p. 217.

[20] Recall that in 146 B.C. the Romans had razed Carthage and Corinth to the ground.

[21] There are good reasons to place him instead as early as the first century A.D.; see [Knorr: AS]. In any case, the deciphering of cuneiform texts has caused a drastic revision in our estimate of Diophantus’ originality, since it shows that the methods he describes had long been in use in Mesopotamia.

have not reached us otherwise, and Theon of Alexandria, whose editions of Euclid's *Elements* and *Optics* have survived through the centuries.[22] The definitive end of ancient science is sometimes dated to 415, the year in which Hypatia, the daughter of Theon and herself a mathematician who wrote commentaries on Apollonius, Ptolemy and Diophantus, was lynched for religious reasons by a fanatical Christian mob in Alexandria.

Because only a few works and fragments, often not exactly datable, are left from the extraordinary wealth of Hellenistic science, we will describe its essential characteristics without always following a timeline.[23] We will concentrate on the third and second centuries B.C., but when documents from that period are lacking we will use later ones. In using documents from the imperial period great caution is necessary, because, as we shall see, scientific methodology had regressed profoundly. When we discuss certain political and economic aspects of the scientific revolution it will of course be essential to differentiate between the period of independence of Hellenistic states and the Hellenistic tradition within the Roman Empire.

1.3 Science

A coarsely encyclopedic organization of knowledge risks appearing to validate the existence of a multitude of sciences, each equally worthy, each characterized by its particular object of study: chemistry, computer science, ornithology, mathematics, trichology, and so on. In this model it is enough to define an object of study and choose a name (possibly of Greek origin) in order to create a new science, understood as a container in which are to be placed all the true statements concerning the specific object chosen. Occasionally, in fact, some have felt that just a bit of Greek is enough, without even the object of study: thus were born, for example, parapsychology and ufology.[24]

---

[22]Heiberg identified Theon's edition with the one transmitted in almost all our manuscripts of the two works of Euclid, but this identification has been contested; see [Knorr: PsER], [Jones], [Knorr: WTE].

[23]Among general books on the history of ancient science it's worth mentioning [Enriques, de Santillana], which still makes interesting reading, though many specific arguments are outdated; the succint [Heiberg: GMNA], which summarizes the contents of extant works; [Farrington]; [van der Waerden: SA]; and the lectures in [Neugebauer: ESA], those about Mesopotamia being especially interesting. [Pauly, Wissowa] is an irreplaceable reference work on ancient science and indeed on classical civilization, while [Sarton] can still be useful for its bibliographical references.

As anthologies of sources we cite [Cohen, Drabkin] and [Irby-Massie, Keyser].

For quick and trustworthy information about individual scientists, ancient and modern, one can use [DSB].

[24]Since UFO stands for "unidentified flying object", the word ufology means approximately "knowledge about unknown flying objects", and is therefore a "science" whose content is void by definition. Similar considerations hold for parapsychology.

In this view, the history of science is the union of the histories of all particular sciences, each being understood as a timetable of "acquisition of truth" in the particular field considered. Naturally, those who adopt this view have little interest in the history of science: that is the case with many historians, who spare for science a nod or brief mention, if that.

Although there have been much more complex philosophical elaborations, the coarse model just described was widespread among scientists at least until the first decades of the twentieth century. The constant and rapid modification of scientific principles, particularly in physics, eventually made untenable the view that science is a collection of statements holding true with certainty. Indeed, this view forces one to consider nonscientific all superseded theories. So long as it was a matter of bodies of knowledge that, more often than not, dated from earlier centuries, their demotion had been accepted painlessly enough; but with the new pace of scientific development the same criterion would imply exclusion from the ranks of science of all but the most recent results. This seemed unacceptable to scientists, probably because it would have meant that their own results would inevitably be some day relegated to the category of nonscience. It became clear, in other words, that a good definition of science must allow one to regard as scientific even mutually contradictory assertions, such as the principles of classical mechanics and those of relativistic mechanics.

At the same time, the usefulness of the term "science" evidently lies in the possibility of telling scientific knowledge apart from other valid types of knowledge, such as historical knowledge or empirical technology. Since what distinguishes science from other forms of knowledge is not the absolute validity of scientific assertions, the question remains:

What is science?

At first glance one might think of two different methods for answering this question: either describing the characteristics of science as it arose historically, or approaching the problem theoretically. But a slightly closer analysis easily shows that each of the two methods presupposes the other. One cannot approach the problem of characterizing the scientific method without being familiar with the science that did in fact evolve through the centuries, that is, without knowing the history of science. On the other hand, any history of science must obviously presuppose a definition, if perhaps tacit or even unconscious, of science.

The only way to avoid this apparent vicious circle is probably to follow a spiral path, alternating between both methods so they justify each other in turn.

Since our primary aim is historical rather than philosophical, and since it is better to work with explicit rather than hidden assumptions, we will present and illustrate in this section a definition of science without discussing its validity. The definition's aim is simply to pin down the object of study of the next few chapters, and to clarify our criterion for selecting the works that will be regarded as scientific. Once this definition has done its job, helping us identify a corpus of relatively homogeneous works, we will turn in Chapter 6 to the problem of characterizing science, asking what were the origins and features of the Hellenistic scientific method as it developed historically. I believe that a better understanding of the method used by ancient scientists has essential relevance to the history of modern science (this will be fleshed out with examples in later chapters) and that it can be an important source of insight in the discussion of current science (a point that lies beyond the scope of this work).

To reach our definition of science, we start by observing that some theories that everyone regards as scientific, like thermodynamics, Euclidean geometry, and probability theory, share the following essential features:

1. *Their statements are not about concrete objects, but about specific theoretical entities.* For example, Euclidean geometry makes statements about angles or segments, and thermodynamics about the temperature or entropy of a system, but in nature there is no angle, segment, temperature or entropy.

2. *The theory has a rigorously deductive structure;* it consists of a few fundamental statements (called axioms, postulates, or principles) about its own theoretical entities, and it gives a unified and universally accepted means for deducing from them an infinite number of consequences. In other words, the theory provides general methods for solving an unlimited number of problems. Such problems, posable within the scope of the theory, are in reality "exercises", in the sense that there is general agreement among specialists on the methods of solving them and of checking the correctness of the solutions. The fundamental methods are proofs and calculation. The "truth" of scientific statements is therefore guaranteed in this sense.

3. *Applications to the real world are based on correspondence rules between the entities of the theory and concrete objects.* Unlike the internal assertions of the theory, the correspondence rules carry no absolute guarantee. The fundamental method for checking their validity — which is to say, the applicability of the theory — is the experimental method. In any case, the range of validity of the correspondence rules is always limited.

Any theory with these three characteristics will be called a scientific theory. The same term will be used for some other theories, which we may call "of a higher order". They differ from the theories we have been considering in that they possess no correspondence rules for application to the real world — they are applicable only to other scientific theories. That

is the most common case in contemporary mathematics. Although some who work at the higher levels may tend to lose sight of it, the relationship between theory and reality does not change in any essential way: albeit indirect, it is nonetheless guaranteed by the same mechanism of formation of theories.

Exact science will mean to us the totality of scientific theories.

A simple criterion to verify whether a theory is "scientific" is to check whether one can compile an exercise manual; if that is not possible, it's certainly not a scientific theory.

The immense usefulness of exact science consists in providing models of the real world within which there is a guaranteed method for telling false statements from true. Whereas natural philosophy failed in the goal of producing absolutely true statements about the world, science succeeds in guaranteeing the truth of its own assertions, at the cost of limiting itself to the realm of models. Such models, of course, allow one to describe and predict natural phenomena, by translating them to the theoretical level via correspondence rules, then solving the "exercises" thus obtained and translating the solutions obtained back to the real world. There is, however, another possibility, much more interesting: moving freely within the theory, and so reaching points not associated to anything concrete by the correspondence rules. From such a point in the theoretical model one can often construct the corresponding reality, thus modifying the existing world. (See Figure 1.1.)

Thus scientific theories, even if created for the purpose of describing natural phenomena, are able to enlarge themselves by means of the deductive method, and as a consequence they usually develop into models of areas of technological activity. *Scientific technology*, characterized by purposeful planning done inside some scientific theory or other, is intrinsically connected to the methodological structure of exact science, and cannot but arise together with the latter.

One of the goals of this work is to corroborate this last assertion — which openly contradicts the common notion that science in "Antiquity" lacked technical applications — by analyzing Hellenistic science and technology. We will also try to clarify all the methodological characteristics mentioned so far by examining the first scientific theories, which arise precisely in Hellenistic times.

Every scientific theory has a limited realm of use; it can in general be used to model only phenomena that are not "too far" from those that motivated its creation. Theories that prove inadequate in describing new sets of phenomena must be replaced for the purpose; but they remain scientific theories according to our definition, and can continue to be used inside their own sphere of validity.

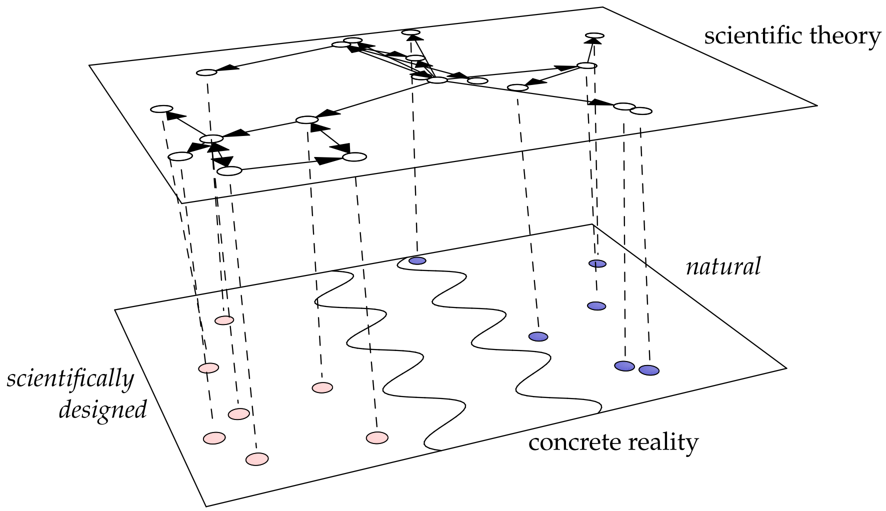


FIGURE 1.1. The role of scientific technology. Dark-shaded circles on the concrete (lower) plane represent objects from nature or prescientific technology. Their counterparts on the theoretical (upper) plane are linked via logical deductions (arrows) to many other constructs, which may or may not have a concrete counterpart. Some of these theoretical constructs give rise, via correspondence rules (dashed lines), to new concrete objects (lightly shaded circles on the lower plane).

The structure of science is enriched by links of various types between different theories; sometimes one theory manages to include another, but more often there is partial overlap between their spheres of applicability.

Two essential aspects of exact science, closely connected to one another, are its methodological unity and its extreme flexibility in considering new objects of study. The scientificness of a discipline does not depend on the kind of thing it studies, but on whether scientific theories can be applied to that thing, and the answer of that question is a historical given. For example, the study of chemical reactions, which had been purely empirical for centuries, acquired the character of exact science as soon as it started to approach the problem using a scientific theory (based on postulates such as the well-definedness of elements, their quantitative preservation and their combination in fixed proportions).

The most significant divisions of exact science are those based not on the phenomena under study, but on the theories brought to bear, each of which generally applies to an enormous set of phenomena seemingly unrelated to one another (other than through that theory).

Science will mean to us primarily exact science. The so-called empirical sciences are to an extent similar to exact science, and distinct from various

types of prescientific knowledge, above all because their development is based on the experimental method and is carried out by specialists whose work, unlike philosophical speculation on the one hand and professional activities on the other, has the purpose of simply acquiring knowledge. One can talk about theories in connection with the empirical sciences, inasmuch as these sciences too are based on the construction of specific theoretical concepts, but these empirical theories do not satisfy the second property in our definition of a scientific theory, lacking as they do the rigorously deductive structure that characterizes exact science. Empirical theories, because they cannot be extended via the deductive method, can be used only as models for a specific set of phenomena and do not produce results exportable to other spheres. Therefore it is possible and convenient to classify empirical sciences by their concrete objects of study, in contrast with the situation for exact science.

The assignment of a privileged status to current scientific theories, as if they represented the standard of truthfulness, is a distorting lens that has often in the past led historians of science to misevaluate and misinterpret ancient science. This can best be clarified with an example. Among many possible quotations we select one from Max Jammer:

> Even Archimedes, the founder of statics, has little to contribute to the development of the concept of force. His treatment of mechanics is a purely geometric one[.][25]

Archimedean statics is a scientific theory that allows the solution of pretty much the same problems as modern statics, which was born from the translation of Archimedes' theory into a Newtonian language, where the concept of force plays a fundamental role. But the concept of force is not a necessity of nature, as demonstrated by the several formulations of mechanics that do not involve it at all. To regard it as a limitation of the Archimedean theory that it contributed little to the development of the concept of force is like regarding it as a limitation of the Greek language that it contributed little to the development of the word "horse".[26]

If we conceive history of science as the history of successive episodes of acquisition of truths bearing directly on natural phenomena, we cannot but be led to the practice, often adopted by historians, of confining all mention of science to inessential remarks or footnotes; but if scientific theories are conceived as theoretical models of sectors of human activity, they clearly acquire fundamental historical interest. On the one hand, their

[25][Jammer: CF], p. 41.

[26]The culminating irony is that the search for "purely geometric" formulations of mechanics has been a constant from Lagrange to Einstein, whose general theory of relativity has allowed a "purely geometric" formulation of the theory of gravitational forces.

study can supply precious information about the sectors of activity for which the models themselves were created and used; on the other, they are cultural products that can be situated in relation to other aspects of the civilization that created them.

At the other extreme, the contextualization of scientific theories can have the side effect of obscuring what is special about scientific knowledge. This is one of the outcomes of a process that probably started with Thomas Kuhn's famous book[27] and culminated in the complete relativism of many authors. Kuhn's work comprises many of the ideas we have discussed, but what he calls a scientific paradigm is a much more general notion than a scientific theory having the three properties we listed on page 17. It includes forms of knowledge, such as Pythagorean mathematics, Aristotelian physics and various medieval theories, which are excluded from the definition we use. One reason to keep the distinction in sight is that a paradigm such as Aristotelian physics may provide a useful system to frame known reality,[28] but cannot be used to plan different realities, since it lacks a rigorously deductive structure and is thus unable to extend itself via the deductive method. Therefore there is no obvious relationship between technology and science in the very broad sense that Kuhn gives the word. Also the problem of the birth of science cannot be posed in the scope of Kuhn's terminology.

The definition of science proposed here will appear overly restrictive to many. There is no question that it excludes many important conceptual constructs that are often called scientific. The use of a restrictive definition is not intended to deny the importance of other cognitive methods — among which are those used in this book. Its purpose is to focus on a particular intellectual instrument, which, as we will attempt to show, is inherited from Hellenistic culture and was essential in building what we call modern civilization.

1.4 Was There Science in Classical Greece?

The thesis that science, in the particular sense we have given this term, is a product of Hellenistic civilization obviously should not be taken to mean that no element of the scientific method appeared before 323 B.C. — the conventional boundary, which for our purposes should perhaps be moved slightly earlier. Many characteristics of science certainly appeared in the

[27] [Kuhn: SSR].

[28] Directly perceptible "physical" properties are better described by Aristotelian physics than by later science. See [Bozzi].

preceding period, especially in Greek geometry and astronomy during the fifth and fourth centuries. Nonetheless, we will try to show that:

- the method that we have called "scientific" was not fully present in the ancient empires, nor yet in fifth century Greece or in the works of Plato and Aristotle;
- the boom in scientific theories took place during the third century B.C. and was an essential feature of Hellenistic civilization;
- if one must identify a turning point in the process of formation of the new method, the best candidate seems to be the foundation of Alexander's empire.

The assertion that classical Greek culture had not created science needs clarification.

Usually the comparison between modern and ancient scientific thought is established primarily in terms of modern physics and the ideas of the Greeks, most often presented as a conceptual evolution that, starting with the Ionian school, seems to essentially end with Aristotle. Framing the comparison in these terms allows one to pay homage to "Greek thought", to which we all recognize ourselves heirs, while maintaining an obvious, if implicit, attitude of benevolent superiority. Today's physicist, talking about atoms, is often aware of using a term introduced by Leucippus and Democritus almost twenty-five hundred years ago. She recognizes the merits of these ancient thinkers who, although lacking our experimental means and refined conceptual tools, nonetheless intuited a theory that foreshadows the modern one. This acknowledgement is gladly made, because it allows one to display one's humanistic culture, while savoring a pleasant sensation of superiority, based on the belief that the old atoms, being born of pure philosophical imagination, had in fact very little in common with the homonymous objects of modern physics. The debt to ancient science explicitly acknowledged by modern science generally stays within similar limits. Even a scientist of vast learning like Heisenberg, in sketching a comparison between Greek thought and modern physics, after having dwelt at length on pre-Socratic thinkers (with interesting things to say) jumps from Aristotle to modern science, without devoting a single word to the development of ancient exact science, which took place chiefly after Euclid.[29]

From now on we will instead discuss Hellenistic science, referring only occasionally to its classical antecedents. This is because these antecedents are not really relevant to our subject. The atomic theory of Leucippus and

[29] [Heisenberg], Chapter 4.

Democritus, for example, has of course tremendous interest for the history of thought, but it does not seem to be a scientific theory in the sense we gave this expression in the preceding section, because, as far as we know from surviving fragments, no theorems of atomic theory were proved by the ancient atomists, nor any true experiments carried out.

However, we stress the following points:

- Explanations of phenomena by means of theories that involve nonobservable entities, such as the atoms of Leucippus and Democritus, is a step of enormous importance toward the construction of scientific theories.
- Many of the ideas destined to become keystones in science, Hellenistic and modern alike, were born from the Greek thought of the classical period. This is the case with mechanistic determinism, which seems to go back to Leucippus,[30] and the distinction between primary and secondary qualities, which appears in Democritus[31] and became an essential foundation for the formulation of quantitative theories of phenomena such as sound, color and the chemical properties of substances.
- Even some more specific notions that are often considered scientific already appear in the thought of the so-called pre-Socratic thinkers.[32] Science is indebted to the Greeks not only for the general notion of atoms and for the word, but also for ideas such as the chaotic motion of atoms[33] (which, developed in the Hellenistic period and revived in modern times, was essential in the creation of the kinetic theory of gases) or the presence of "hooks" that allow atoms to connect together,[34] a didactic image still used in elementary chemistry books.

For another example, consider the "bucket experiment", one of whose variants consists in spinning a bucket full of water in a vertical plane very

[30] As reported by Aetius (Stobaeus, *Eclogae* I, iv §7, 72:11–14 = [DG], 321b:10–14 = [FV], II, 81:3–6, Leucippus B2).

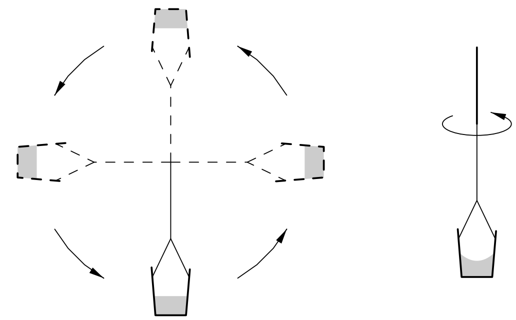
[31] See for instance Stobaeus, *Eclogae* I, xvi §1, 149:10–16 = [DG], 314b:1–10 = [FV], II, 112:28–32, Democritus A125.

[32] Among the philosophers traditionally called pre-Socratic we will be particularly interested in Democritus, who in fact survived Socrates by several years.

[33] See, for example, Diogenes Laertius (*Vitae philosophorum*, IX §31 = [FV], II, 70:26 – 71:5, Leucippus A1), where the idea is attributed to Leucippus. It would be interesting to know the origin of the notion of chaotic motion of atoms. A superb passage in Lucretius about the disordered motion of dust lit by a sunbeam (*De rerum natura*, II:112–141) hints at the type of phenomena that might have suggested the idea. Lucretius mentions the disordered and extremely fast motion of atoms as the ultimate cause of the progressively slower motion of larger particles. It is interesting to compare the lucid explanation reported by Lucretius with the vitalist explanation given in 1828 for a similar phenomenon by the famous discoverer of "Brownian motion"; see [Brown].

[34] The existence of atoms with hooks was postulated by Democritus, as we know from Aristotle's (lost) book *On Democritus*, a passage of which is reported by Simplicius (*In Aristotelis De caelo commentaria*, [CAG], vol. VII, 294:33 – 295:24 = [FV], II, 93:37 – 94:2, Democritus A37).

fast: the liquid does not fall out. Or, if the bucket is kept upright and spun around its own axis, the surface of the water takes on a characteristic concave shape. Either way one sees that the equilibrium configuration of



the water depends not only on the bucket's position with respect to the ground, but also on its state of movement, making it possible to assign an absolute meaning to the statement that the bucket is "in motion", at least if the motion is rotational.

Such remarks, which today we phrase in terms of centrifugal "force", must have made an important contribution to the birth of dynamics, but they are not true experiments, just qualitative observations, so it's not surprising that they predate the rise of scientific theories: indeed they must go back to deep Antiquity. The first documented use of the bucket experiment for theoretical ends seems to be due to Empedocles.[35] Centrifugal "force" was brought to bear in a cosmological context by Anaxagoras, among others; he explained the origin of our world by invoking the separation of the various types of matter caused by the centrifugation of an immense vortex.[36] The very idea of vortices in cosmology was to remain a constant throughout the history of thought: Kant's and Laplace's theories on the formation of the solar system seem to have been influenced by it.

Certainly, many ideas of the pre-Socratic philosophers seem to be akin to the later, Hellenistic, scientific method. However, in no case is there documentation for the use in the classical period of full-fledged hypothetico-deductive theories or the experimental method.[37]

[35] See Aristotle, *De caelo*, II, xiii, 295a:13–22 = [FV], I, 295:31–37, Empedocles A67. According to the passage, Empedocles used the bucket experiment to make some argument about the immobility of the Earth.

[36] Simplicius, *In Aristotelis Physicorum commentaria*, [CAG], vol. IX, 35:13–17 = [FV], II, 36:19–24, Anaxagoras B9.

[37] The tale that Pythagoras made experiments with sound, studying for instance the change in the pitch of a string as the tension varies, is widespread, but the earliest source we have for it dates from about 100 A.D. (Nicomachus of Gerasa, *Manual of harmonics*, 6). This report is unreliable, not

To show the qualitative leap from Aristotelian natural philosophy to Hellenistic science, we recall that Aristotle wrote:

> If, then, [a force] *A* moves *B* a distance *D* in a time *T*, it does not follow that *E*, being half of *A*, will in the time *T* or in any fraction of *T* cause *B* to traverse a part of *D* that is to the whole of *D* as *A* is to *E*.... Otherwise one man would move a ship, since both the motive force of the ship-haulers and the distance that they all cause the ship to traverse are divisible into as many parts as there are men.[38]

Without reconstructing all of Aristotle's reasoning, we focus on certain key features of the method he uses to approach the problem of motion (and other "physics" questions). Aristotle's problem is determining the quantitative relationship between force, time, and displacement. With the scientific method one can solve such problems in one of two ways: either by supposing a relation given "in principle" (in which case experiment plays an essential role in checking whether the real phenomena whose model one wishes to build do in fact occur in the way predicted by applying the correspondence rules to the stated principle), or else by deducing the desired relationship inside a preexisting scientific theory, using the deductive method. But Aristotle cannot use either the deductive method or experiments, for he does not have, and does not wish to build, a scientific theory. The forces, times and displacements that he talks about are not in fact entities internal to a theory, but he conceives them as concrete objects, whose mutual relations can be understood via philosophical speculation.

He mentions an empirical datum (the impossibility of a single person moving a ship), but the decisive argument is that the portion of the force under consideration acts differently depending on whether it is in isolation or as part of a whole, because in the second case the part exists only potentially. For all intents and purposes, the empirical fact is mentioned just by way of illustration. The real game is to deduce quantitative statements about particular physical phenomena directly from general philosophical principles, derived from qualitative observations of nature.

Archimedes' confutation of Aristotle's argument, reported by Plutarch and Proclus, was very persuasive. According to the tradition they transmit, Archimedes designed, within his scientific theory of mechanics, a device that enabled a single man — himself or King Hiero II, depending

only for chronological reasons and because of the general tendency neo-Pythagoreans like Nicomachus had of backdating all knowledge to Pythagoras, but also because the same experiments are attributed not to Pythagoras but to his followers by Plutarch (*De animae procreatione in Timaeo*, 1020F–1021A) and by Porphyry (*In Harmonica Ptolemaei commentarius*, 119:13 – 120:7, ed. Düring). Iamblichus copied the story from Nicomachus (Iamblichus, *Vita pythagorica*, §§115–119) but on another occasion he follows Porphyry's version (*In Nicomachi arithmeticam introductionem*, 121).

[38] Aristotle, *Physica*, VII, v, 250a; loosely based on a translation by R. P. Hardie and R. K. Gaye.

on the version — to drag into the water a ship towed up onto dry land in the Syracuse harbor; Proclus specifies it was a full-laden three-masted ship.[39] The machine itself carried out the division of force that Aristotle had judged impossible, and which indeed had probably never been achieved before for a ship. This was a very effective way to demonstrate the superiority of "scientific" method, in the sense already explained, over natural philosophy. Rather than reflecting the world in philosophical speculation, the scientific method had changed the world, by allowing the design of a machine that eliminated the impossibility observed by Aristotle.

The methodological value of the experimental demonstration narrated by Proclus and Plutarch, which stands out most clearly in comparison with the Aristotelian quotation, does not of course depend on whether Archimedes explicitly wished to confute Aristotle[40] or whether the reported details are historically accurate. The essential point is that, since we know that Archimedes had in fact developed the possibility of designing machines with high mechanical advantage, the story is not a legend without foundation. It reflects on the one hand the type of achievement made possible by Archimedean mechanics, and on the other a widespread interest in this new technology, and in these respects it is completely believable.[41] But instead, the ship episode is usually recounted in the context of the legendary and anecdotal treatment of Archimedes' persona, which deprives it of its true meaning.

One often reads that Greek scientists invented statics but not dynamics. That is, they knew the equilibrium conditions of bodies, but not their laws of motion. Such statements give the impression that ancient scientists, because of their "contemplative" nature, spent their time observing objects in equilibrium, without ever moving them. This impression can hardly be reconciled with the tale of Archimedes designing and using a machine that enabled a single person to drag a ship. The truth is that in the third century B.C. "our" dynamics had not been developed; but the quantitative theory of machines such as winches and cogwheels with mechanical advantage, which had most certainly been developed, must be considered as a form of dynamics, since the point of such machines is not just equilibrium. The notion that Archimedes invented statics but not dynamics comes from the fact that our statics essentially coincides with his, but the same cannot be

[39] Proclus, *In primum Euclidis Elementorum librum commentarii*, 63, ed. Friedlein. The same episode is told by Plutarch in a slightly different way (Plutarch, *Vita Marcelli*, xiv §8).

[40] C. Mugler argues for this conscious reference to Aristotle's passage; see [Archimedes/Mugler], vol. I, Introduction, p. xi).

[41] The origin of the tradition was probably not a true experimental demonstration, but the wonder aroused by the machine designed by Archimedes to launch the huge ship *Syracusia* (Athenaeus, *Deipnosophistae*, V, 207b).

said about our dynamics. Archimedes' mechanics — literally, his "science of machines" — was nonetheless a scientific theory, which dealt with both equilibrium and motion, even though, like all scientific theories, it applied only to phenomena that lie within a limited realm.

The situation was probably analogous to that of our thermodynamics of reversible transformations. Since we only know how to define the thermodynamical state of a system when it is in equilibrium, we only know how to study thermodynamical transformations by approximating them by a series of equilibrium states. In this way we study thermodynamic cycles that model for example what happens inside an internal combustion engine; the model, within certain limits, applies, but that does not mean that our internal combustion engines remain in equilibrium, nor has anyone ever thought of naming "thermostatics" the study of such evolutions through states of equilibrium.

Likewise, the main mechanical problem of the third century B.C. was the study of machines that, while carrying out work, could be thought of as if the forces in question were at all times "almost in equilibrium". That is indeed the case of a pulley that lifts a weight slowly. Problems regarding mechanical systems of that type (in particular the calculation of their mechanical advantage[42]) can be solved using Archimedean mechanics. Our "classical mechanics" is an improvement on the Archimedean theory because it subsumes it and can be applied in many cases where the preceding assumptions are not valid. But this difference is of the exact same nature as the difference that makes, say, relativistic mechanics an improvement on the classical version. The essential qualitative leap, from natural philosophy to science, has already taken place with Archimedes. After that it's "just" a matter of developing theories that can model increasingly more general classes of phenomena; the path is already laid out, as shown by the fact that several Hellenistic scientific theories, such as hydrostatics, geometric optics, and the theory of simple machines, have been absorbed essentially without change into modern science.

We will come back to successive developments in Hellenistic mechanics and their relationship with Newtonian dynamics in Chapters 10 and 11.

1.5 Origins of Hellenistic Science

Why was science born precisely at the same time as Hellenistic civilization, with Alexander's conquests?

[42]We will return to this point in Section 3.3.

Probably one important factor was the new relationship established between Greek civilization and the ancient Egyptian and Mesopotamian civilizations. The Greek cultural tradition, which in the classical period had created historiography, theater, political democracy and the masterpieces of literature and art that we all know, and also natural philosophy as we have already discussed, was obviously essential. But what did the creators of this stupendous civilization have to learn from the Egyptians, for example? We must let sink in the (long ignored) fact that, despite all the achievements of their culture, the Greeks of the classical age were still behind the Egyptians and Mesopotamians from the technological point of view. Recall what Charles Singer wrote in the epilog of the second volume of his *History of Technology*:

> Whatever view be taken of the beauty and interest of the art, literature, ethics, and thought of Greece and Rome, it can no longer be held true that their technology was superior to that of the ancient empires.... The curve of technological expertness tends to dip rather than to rise with the advent of the classical cultures. This will become apparent if the relevant chapters of volume I be compared with the corresponding chapters in the present volume.... Greece and Rome ... rose to their might by the destruction of the more ancient civilizations that they displaced.... [T]he rise of the Hellenic and Roman peoples represents a 'heroic age' which, like many heroic ages, was primarily a victory of barbarians over an effete but ancient civilization.[43]

This is one of the conclusions of an influential work on the history of technology, filled with articles by the greatest experts in their fields and thus deserving of careful consideration. But one is struck by the constant and mechanical merging of Greece and Rome into an indivisible unit. It is impossible to see in what sense Greece might have destroyed older civilizations, or in what sense the Hellenes can be called barbarians. Moreover, it's easy to document (and we shall do so) that Egypt's technological level rose under the Ptolemies. Singer's conclusion seems to have been reached by melding together three elements of wildly unequal worth:

- the conclusion — interesting and very valuable, in that it draws upon a huge fund of historical research on numerous technological areas — that the technology of the ancient empires was superior to classical Greece's (the point that concerns us) and Rome's;
- the fairly obvious fact that Rome rose to its might by the destruction of more advanced civilizations;

[43][HT], vol. II, pp. 754–755.

– the clichés that lie at the root of the uncritical association of Greece and Rome into an indivisible unit and of the use of "Greek civilization" to refer basically to the classical era, ignoring the originality of Hellenistic civilization.

We can in any case take it as certain that the Greeks who moved into Egypt and Mesopotamia at the time of Alexander's conquests found there a level of technology higher than their own. The technological development of all three cultures — classical Greece, Egypt and Mesopotamia — having proceeded by a gradual accumulation and transmission of empirical knowledge,[44] it is natural that the extra millennia would give the two older civilizations a technological advantage, unsurmountable except in the presence of a qualitative methodological leap.

The Greeks had always been interested in the traditions of older civilizations, with which they had been in contact for centuries. It is not by accident that the beginnings of Greek mathematics are credited to Thales and Pythagoras, both of whom were said to have lived in Egypt (and Pythagoras also in the East). But in the Hellenistic period the contact becomes much closer.[45] The Greeks who moved to the new kingdoms that arose from Alexander's conquests had to administer and control these more advanced economies and technologies with which they were not familiar; their one crucial advantage and guide consisted in the sophisticated methods of rational analysis developed by the Greek cultural tradition during the preceding centuries. It is in this situation that science is born.

Actually there are indications that at the time Alexander formed his empire many features of the scientific method were already in place. Since no scientific work from that period has survived, this is difficult to prove, but the progress achieved by scientists such as Eudoxus of Cnidus a few decades before Alexander seems to show elements of continuity with the following period. However, although on the basis of surviving documents this continuity seems to be well-attested regarding individual instruments internal to mathematics and astronomy, the scientific explosion, that is to say the creation of many different scientific theories understood as models of the real world based on systems of explicitly specified assumptions, seems to be new to the Hellenistic era.

[44]Of course the pace of technological development never stayed constant. Mesopotamia, for example, enjoyed a surge in the development of water, agricultural, and building technologies during the fourth millennium B.C., with the appearance of the first cities. But this and similar bursts are to be taken in a relative sense; they required many centuries. We will return to this question at the beginning of Section 7.2.

[45]To an extent that is impossible to quantify, this change preceded, and even helped motivate, Alexander's campaigns: interactions between Greece and the territories of the ancient empires had been intensifying throughout the fourth century, again thanks to increased migration.

Note that the application of the scientific method requires the ability to use simultaneously two levels of discourse, one internal to the theory and one concerning concrete objects, and to move between the two levels by means of what we've called "correspondence rules". It is enticing to conjecture that this ability was favored, in the territories belonging to Alexander's empire, by the simultaneous presence of two cultures and by the ability developed by Greek immigrants to use both at the same time according to their goals, in particular by reworking into their conceptual framework the large mass of empirical knowledge inherited by the Egyptian and Mesopotamian cultures.[46]

One example of the ability of Hellenistic science to provide a rational framework within which the knowledge of ancient civilizations could be used to advantage is given by the organization, under the Ptolemies, of the immense labor of waterworks that consisted in the regulation of the Nile floods. The Egyptians had millennia of experience with this problem; it was the very problem that had led to the creation of Egypt as a unified state.[47] The Ptolemies organized the necessary labor by using many Egyptian experts, but entrusting the general administration of the project to Greek engineers. We shall see what these engineers were able to achieve.

[46]Incidentally, in later eras, an analogous mastery of two cultures — that of one's ethnic group and the majority culture of the surrounding population — has been a characteristic of the Jews, to whom we also owe many key scientific results.

[47]Karl Marx remarked that the Egyptian state, and indeed the state structures of many ancient riverside civilizations (in Mesopotamia, in the Indus Valley, by the Yellow River), arose from the need to coordinate the labor of irrigation and dam building. This observation was the starting point for Karl Wittfogel's monumental studies on "hydraulic civilizations" and "hydraulic despotism" (see [Wittfogel]). Beyond his (highly ideologized) theories, the essential role played by hydraulic problems in the formation of states is widely recognized nowadays. The fact that the Greeks, in a few years, had surpassed in hydraulic works the most ancient "hydraulic civilizations" shows clearly how powerful the new scientific method was.