La Rivoluzione Dimenticata (The Forgotten Revolution)

by Lucio Russo

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[This remarkable book, published by Feltrinelli in Milan, first in 1996 and then in a new edition in 2001, is still available only in Italian. An English language edition is in preparation, and will appear with Springer Verlag. The excerpt below, Chapter I, is translated by Mark A. Peterson after correspondence with the author.]

1 The Birth of Science

1.1 The suppression of the scientific revolution

The central role of science in the development of our civilization is generally recognized. One might therefore expect that its birth, the scientific revolution, would be considered a fundamental turning point in human history. Instead, the importance of this event is almost never noticed. The history of scientific thought typically obscures it, by blurring the differences among Hellenistic science, the pre-scientific knowledge of ancient Egyptian and Mesopotamian civilizations, and the natural philosophy of classical Greece. Books on ancient history usually say nothing about it at all. Most of the time we are told only that in the Hellenistic period certain "sciences" flourished. One can typically find more attention to Archimedes or Aristarchus of Samos in a book on the Renaissance, dealing with their rediscovery, than in a book on classical civilization.

The student of the modern age thinks of the Renaissance or the 17th century with an eye to present – what came after. Thus she cannot ignore the importance of the "Rebirth of Science." The student of antiquity, on the other hand, feels obliged (more so in the past, it is true) to compare Hellenism with the supposed perfection of classical Greece, or with Rome. She thus risks judging it either by the measure of the preceding civilization or by that of a civilization which remained substantially uncomprehending of science: in both cases from the point of view of a pre-scientific society.

The result has been, on the one hand, that most people believe that the birth of the scientific method coincides with what is called, and not by accident, the "Rebirth of Science," and on the other hand that, until the last century, the civilization which actually gave us science wasn't even considered worthy of a name: one spoke simply of a "period of decadence" in Greek civilization.

Droysen[1] was the first historian to re-appraise this extraordinary period and to give it a name, in his *History of Hellenism*.

In the last half century many things have become clearer, and today one can find very interesting works on diverse aspects of Hellenistic civilization.[2] They tend to be compartmentalized works, however, and they have not changed the overall picture available to the educated public, according to which Hellenism continues to appear as a period whose cultural heritage is less essential to us than that of the classical period.

It seems that in our collective historical consciousness there has been a kind of suppression of Hellenism, and in particular of the scientific revolution which unfolded in the 3rd century B.C.E. Our culture, anchored in history on the one hand and in science on the other, has recourse to various expedients to hide from itself the importance of the birth of science.

Let us consider three of the greatest figures of the scientific revolution: Euclid of Alexandria, Archimedes of Syracuse, and Herophilus of Calcedonia. What does the modern "educated person" know about them?

About Herophilus, nothing.[3] About Archimedes, she remembers that he did peculiar things: ran naked shouting Eureka!, immersed crowns in water,

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[1] J.G. Droysen, *Geschichte des Hellenismus*, Gotha 1877-1878.

[2] Some of these will be cited in what follows. Among the works most comprehensive on Hellenism, I consider still fundamental M. Rostovtzeff, *Social and Economic History of the Hellenistic World*, Oxford, 1953. A work which is representative of the most recent tendencies is P. Green, *Alexander to Actium: The Hellenistic Age*, London, 1993. As regards Alexandria in particular, much information and above all a useful collection of primary sources is in P.M. Fraser, *Ptolemaic Alexandria*, 3 vols., Oxford 1972, reprinted 1998.

[3] We will consider him below, particularly in Chapter 5.

drew geometric figures while they were about to kill him, and so forth. The infantile anecdotes surrounding him, together with the near unavailability of his works, place Archimedes more among the personages of myth or legend than among other thinkers. The result is that he is remembered, to be sure, but as a legendary person, outside of history. In the end one forgets that this was a scientist from whom we have many writings, and whose results continue to be taught at every level of our educational system, from elementary school, when we learn to calculate the volume of a sphere, to the university when we study the concepts of mechanics or calculus which originate in his works.

Euclidean geometry has remained the basic framework for education in mathematics for a very long time.[4] But Euclid too has been expelled from history. In his case, the opposite mechanism has been used from that of Archimedes: instead of being pushed into legend and anecdote, he has been deprived of every historical connotation, while "Euclidean geometry" is taken for granted, as if it had always been available to humanity. If you do not believe this, try asking your friends what century Euclid lived in. Very few will be able to tell you, although they have studied Euclidean geometry for years.[5] And yet Euclid is one of the most widely read authors in all human history: his most famous work, the *Elements*, has been studied at first hand over a continuous span of 22 centuries, from 300 B.C.E. to the end of the 19th century. Probably no other author so much studied (although today not at first hand) is so little known.

Another of the mechanisms of the suppression of Hellenism, and in particular of the century of its greatest development, the 3rd century B.C.E., consists in attributing its results, particularly scientific and technological ones, to "Ancients," not better specified. 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 dates to "antiquity," that "in antiquity" there was a "precursor" of Copernicus. Further on we will find many other examples.

The difficulty one runs into in trying to form a picture of the events and persons of the 3rd century B.C.E. is inextricably connected to our profound

[4] Since attempts to base mathematics instruction on systems of axioms devoid of geometric content have not worked, there is today a growing tendency not to teach the method of proof in secondary schools at all; I do not believe one can justify calling such instruction 'mathematics.'

[5] This has been the result, at least, of a little investigation of my own among friends and colleagues.

ignorance of this period, which has been almost erased from history.

In the first place, there has not come down to us any historical account of the period from 301 B.C.E. (the date at which the work of Diodorus Siculo[6] breaks off) until 221 B.C.E (the beginning of the History of Polybius). It is not just that we don't have the Hellenistic historical works: even the later work of Titus Livy is missing the second volume, which covered the period 292-219 B.C.E. Tradition has preserved for us the history of classic Greece and the ascendancy of Rome, that is, of those periods which remained points of reference for the late Imperial period and the Middle Ages, but the story of the century of the scientific revolution was forgotten, as civilization returned to a pre-scientific condition.

In the second place, almost all the writings of this epoch are lost. The civilization which, among its many intellectual achievements, bequeathed to us the very idea of a library and of the jealous conservation of earlier thought has been erased, along with its works. We have a few scientific works handed down by Byzantines and Arabs, but Europe didn't preserve a thing. A little has been recovered: a few fragments on papyrus found at Herculaneum[7] are all that we can read of the hundreds of books written by Crisippus, indicated by many sources as the greatest thinker of the age. As fundamental a work as the treatise *On Method* of Archimedes was discovered by great good luck in 1906 by Heiberg (on the famous palimpsest, since lost, and rediscovered in 1998). And thanks to recent papyrological discoveries we can read Menander; but we are speaking of only a few lucky cases.

The extent of the destruction of Hellenistic works has often been underestimated in the past, on the optimistic theory that the surviving works would be the best. It had been thought, that is, that "classical civilization" had handed down to us certain fundamental works which managed to include the knowledge contained in the works which were lost. Unfortunately this optimistic vision turns out to be without foundation. In fact the best works could not be saved, thanks to an automatic mechanism of natural selection during a general regression of the level of civilization. That the same tradition which preserved intact the 37 books of Pliny's *Natural History* ne-

[6]The narration in Book XX of the *Bibliotheca historica* ends with this date; of the succeeding books we have only fragments.

[7]Herculaneum and Pompeii had very close contact with the Hellenistic world until their sudden, unexpected destruction in 79 C.E. The eruption of Vesuvius thus had the effect of preserving precious testimony of Hellenistic art and culture from the destruction of the Imperial period and the High Middle Ages.

glected to hand down to us the few fundamental pages of Archimedes' *On Method* is by itself a proof that we are in just this position. The selections of those who came later privileged the compilations and works written in a language still comprehensible in late antiquity and in the Middle Ages, when civilization had regressed to a pre-scientific level: we have the work of Varro on agriculture and that of Vitruvius on architecture, but not their Hellenistic sources; we have the splendid poem of Lucretius on 'nature', but not the works of Strato of Lampsacus, which according to some indications could have constituted the beginning of true natural science. Even among the true scientific works there seem to be two criteria of selection followed by the Byzantines and by the Arabs, who preserved some of them. Above all the privileging of authors of the Imperial age, whose works are in general inferior methodologically, but are more easily usable: we have, for example, the works of Heron on mirrors, but not the treatise which, according to some sources, was written by Archimedes on the same subject. Among the works by individual authors the more accessible ones were preferred, in general, and often just the initial parts of them: we have the Greek text of the first four books, the more elementary ones, of the *Conics* of Apollonius, but not that of the next four books (three of which are preserved in Arabic); we have translations into Latin and Arabic of the work of Philo of Byzantium on the experimental demonstations of pneumatics, but we don't have any of his theoretical works, which explained the principles of the theory. We will see in the following other examples of these criteria of selection.

In the third place, until recently there had been no systematic excavations of the centers of Ptolemaic Egypt. Even in the 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 from papyri found in the last century. These have been accidental recoveries, usually discarded sheets used as "waste paper" by the embalmers.

Finally, in the fourth place, apart from a few events of diplomatic-military history handed down to us by the Romans, and the kind of juridical information recoverable from inscriptions, for example, one knows next to nothing about the other Hellenistic kingdoms. Our deficit of information is particularly serious regarding the Seleucid kingdom (which included Mesopotamia), since various indications lead one to think its contribution to scientific development could have been comparable to that of Ptolemaic Egypt. Our ignorance is in part due to the fact that parchment and papyrus are preserved for millenia only under exceptional climatic conditions, like those which have preserved the papyri found in some parts of Egypt. Hellenistic Mesopotamia still used, in addition, cuneiform writing on clay tablets, a very durable writing surface, but this fortunate circumstance seems not to have yielded very much. As Rostovtzeff has written:

> "We know much more about Babylonia than about the other oriental regions, thanks to the recovery of a small number of Greek inscriptions and from the ruins of a few buildings of the Hellenistic period. But the principal source of information consists in thousands of cuneiform tablets of the same period, coming for the most part from Babylon and from Uruk. Of these, only the smallest fraction have been read and published, still fewer translated..."[8]

Perhaps the phenomenon which we have called "suppression" is a deep phenomenon of our culture. It is not just that the cuneiform tablets are not read – even the Hellenistic writings which have come down to us are often not easy to find in accessible editions.[9]

We will seek to characterize the origin of this phenomenon in the course of this book. In these circumstances, if the scarcity of documentation makes it difficult to prove any thesis, on the one hand, it should not be too surprising if, on the other hand, certain current interpretations should prove to be erroneous. Paying close attention to Hellenistic scientific culture without "suppressing" it may produce some surprises, and may force us to modify many accepted ideas about "antiquity."

1.2 Hellenism

To give meaning to the assertion that science was born with Hellenism, it is essential to have some agreement on the meaning of "Hellenism" and of "science." This section and the next are dedicated to the definition of these two terms.

Let us begin with the demarcation in time and space of that civilization which interests us, and of some of the principal protagonists of the scientific

[8]M. Rostovtzeff in *Cambridge Ancient History*, Cambridge 1969, vol. 5

[9]For example there exists no critical edition of the fragments of Eratosthenes. The only attempt in this direction, by G. Bernhardy, appeared in 1822. As regards the scientific works in particular, there exists no collection of the classics comparable to the authoritative series dedicated to literary and philosophical works.

revolution. Hellenism, according to the terminology introduced by Droysen and accepted by successive historians, began in 323 B.C.E, with the death of Alexander the Great.[10] The empire which had been Alexander's dissolved upon his death, giving way to various political entities which were governed at first in the name of the emperor by various pretenders to this title, and which soon constituted autonomous kingdoms. The three principal states were:

– Egypt, with its capital at the new city of Alexandria (founded by Alexander in 331 B.C.E.), ruled by the dynasty of the Ptolemies, who governed also Cyprus, la Cirenaica(?), and, in the 3rd century B.C.E., Phoenicia and Palestine;

– the Seleucid kingdom, with its capital at Antioch, which included Syria, almost all of Asia Minor, Mesopotamia, Iran, and, after 200 B.C.E., also Phoenicia and Palestine;

– the kingdom of the Antigonides, which included Macedonia and some of the cities of Greece.

There were also smaller states, like the kingdom of Pergamon, ruled by the dynasty of the Attalides, Pontus and Bithynia. One Hellenistic state of which we know little but which probably had an important role as intermediary between Hellenistic culture and the cultures of India and China, was Bactria, which extended through present day Afghanistan, Uzbekistan, and Tajikistan.

Hellenistic civilization was not the product solely of the Greek inhabitants in those regions which had formed Alexander's empire: it also had contributions from autonomous Greek cities which were distributed all across the Mediterranean. Among the most important autonomous centers were Rhodes, Syracuse, and Marseilles.

Science "exploded" in the course of the 3rd century B.C.E, and it has often been called Alexandrian because its principal center was Alexandria in Egypt. One of the reasons for this supremacy was certainly the policy of the first Ptolemies: particularly important was the work of Ptolemy I Soter (who reigned from 323 to 283) and of Ptolemy II Philadelpho (who reigned from 283 to 246).

[10]Since the essential innovation of the period consists in the realization of Alexander's program of Hellenizing the ancient empires, it might seem more logical to choose the initial date of the expedition (or of the reign) of Alexander. The difference of just a few years is of course inessential, but the slightly macabre choice adopted is an indication of the partial survival even in Droysen of the prejudice against 'Hellenistic decadence.'

Euclid lived and taught at Alexandria, at the end of the 4th century B.C.E. In the first half of the 3rd century B.C.E. Ctesibius lived there, founder of pneumatics, and initiator of the school of Alexandrian mechanics, and Herophilus of Calcedonia, founder of anatomy and scientific physiology.[11] The activity of Aristarchus of Samos, famous above all for having elaborated the heliocentric theory, dates from the same epoch.[12] It is very likely too that Archimedes studied at Alexandria, since even from Syracuse he maintained steady contact through letters with the Alexandrian scientists. Among the scientists of the second half of the 3rd century was Eratosthenes, who was librarian at Alexandria, and who, among other things, accomplished the first true measurement of the size of the Earth. Crisippus, who interests us particularly for his contributions to logic, lived in the same century at Athens, which had remained the principal center for the study of philosophy. The activity at Alexandria of Philo of Byzantium, continuing the work of Ctesibius, dates probably from the end of the century. Straddling the end of the century and the beginning of the next is 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 2nd century B.C.E was Hipparchus of Nicea, active at Rhodes, above all in astronomy.

Beginning in 212 B.C.E (the sack of Syracuse and killing of Archimedes), the centers of Hellenism were defeated and conquered by the Romans. In the course of the 2nd century B.C.E. scientific studies declined rapidly. In particular, scientific activity at Alexandria ceased dramatically in 145-144 B.C.E. when there was a ferocious persecution of the ruling Greek class on the part of Ptolemy VIII (Evergete II), who had just ascended the throne. Polybius says that the Greek population of the city of Alexandria was almost completely exterminated.[14] Athenaeus gives a vivid description of the consequent diaspora of the intellectuals from the city;[15] other sources give a

[11]It has been ascertained that Ctesibius was active during the reign of Ptolemy II Philadelpho. We will return to the problem of dating Herophilus.

[12]We know from Ptolemy that 'the members of the school of Aristarchus' made an observation in 279 B.C.E (*Almagest* III, i, 206). We know besides from Aezius that Aristarchus had been a student of Strato of Lampsachus, who was head of the peripatetic school until 269 B.C.E.

[13]For the dating of Apollonius see G.J. Toomer, *Apollonius of Perge*, in *Dictionary of Scientific Biography*, ed. C. Gillespie, 15 vols., New York 1970-1980, vol. I, pp. 179-193.

[14]Polybius, *History*, XXXIV.

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

few other particulars.[16] There is not enough information to reconstruct the cause of the persecution. Evergete II afterward maintained policies hostile to the Greek community of Alexandria, relying for support on the indigenous element.[17] Since he had already enjoyed the help of the Romans before obtaining the throne (when, exiled by his brother, he had gone to Rome[18]), one may suspect he was used by Rome as an instrument of their policy of expansion in the Mediterranean,[19] which in these years was particularly violent.[20]

The expansion of Rome ended in 30 B.C.E. with the annexation of Egypt, which completed the unification of the entire Mediterranean under the domination of Rome. This event is usually considered the end of Hellenism, followed now by the "Imperial period." From our point of view, however, it is not a particularly significant date. While the golden age of science had been tragically brought to a close over a century earlier, with the end of scientific activity at Alexandria and the Roman conquest of the other principal centers, Hellenistic culture survived into the Imperial period. The former kingdoms were in fact not assimilated, either linguistically or culturally, and from the point of view of technology and economics there were perhaps more aspects of continuity with the preceding period than similarities with the Latin West. For these reasons one continues to use, at times, the term Hellenism to indicate the culture of that part of the Roman Empire in which the dominant language continued to be Greek.

After the interruption occasioned by the wars with Rome, the "pax Romana" allowed for a partial recovery of scientific research between the 1st and 2nd centuries C.E. (the time of Ptolemy, Heron, and Galen), after which the decline was unstoppable. Alexandria, however, continued to be the principal scientific center for centuries. The last scientist of any merit was perhaps Dio-

[16]For example Valerius Maximus tells us that the king surrounded the Greek school and killed everyone found there (*Factorum ac dictorum memorabilium libri*, IX, ii, ext. 5). The few other sources are collected in Fraser, vol II, pp. 216 ff.

[17]The Alexandrians succeeded in driving him out, but he reconquered Alexandria in 127 B.C.E.

[18]See Polybius, *History* XXXI, 20.

[19]This impression seems to be confirmed by an inscription at Delos which contains the dedication of a statue of a general of Evergete II by Roman traders, in recognition of *benefits conceded to them when Alexandria was taken by king Ptolemy Evergete* (i.e., Evergete II). The dedication does not refer to the events of 145-144, but to the episode of 127. The inscription is reported in Fraser, vol. II, p. 217.

[20]We recall that in 146 B.C.E. the Romans razed to the ground both Carthage and Corinth.

phantus, who lived sometime between the 2nd and 4th centuries C.E.[21] The scientific activity documented in the 4th century is not original, but is limited to compilations, commentaries, and redactions of old works. Among the commentators and redactors of this period Pappus, whose *Collections* contains many mathematical results otherwise unknown, and Theon of Alexandria, author of felicitous redactions of the *Elements* and the *Optics* of Euclid, are of particular interest.[22] The end of ancient science is sometimes placed in 415, the year in which the daughter of Theon, Hypatia, herself a mathematician (she wrote commentaries on Apollonius, Ptolemy, and Diophantus) was lynched at Alexandria by a mob of Christian fanatics, for religious reasons.

Since there remain to us only a few works and fragments of the extraordinary development of Hellenistic science, often not datable with exactness, we will seek to describe its essential characteristics without always following its historical development.[23] Our attention will be directed above all toward the 3rd and 2nd centuries B.C.E., but when we lack documents from this period we will use others, dating from the succeeding centuries. When using writings from the imperial period, however, one must use great caution, since we will see that scientific methodology suffered a profound regression. When we point out certain political and economic aspects of the scientific revolution, it will obviously be necessary to distinguish the period of independence of the Hellenistic states from that of Hellenism within the Roman Empire.

1.3 Science

An organization of knowledge of the kind called encyclopedic risks crediting the existence of a multitude of "sciences," all equally worthy, each one characterized by its particular object: chemistry, ornithology, mathematics, computer science, and so on. According to this conception it is enough to choose an object susceptible of knowledge and to invent a name (possibly of Greek origin) to create a new "science," conceived of as a container in which will be placed all the "truths" regarding the specific object selected. Indeed it has sometimes seemed sufficient to some people to put a little Greek into

[21] The deciphering of cuneiform texts has however drastically altered our view of the originality of Diophantus, showing that the methods he describes had been in use for a long time in Mesopotamia.

[22] Heiberg identified the redaction of Theon as the source for practically every manuscript of the two works of Euclid. This identification has been disputed, however.

[23] [The book gives a list of modern sources on the history of science in this period.]

the name, without even having an object: this is the origin of parapsychology and UFOlogy, for example.[24]

According to this idea the history of science is the union of the "histories" of all the particular sciences, each one of which is conceived as a chronology of the "acquisition of the truth" in the particular subject considered. Naturally anyone who shares this view will not be very interested in the history of science: it is a case of many histories, which at most give only a hint of what science is.

Notwithstanding some truly complex philosophical elaborations, the rough idea just described was generally accepted by scientists at least until the first decades of the 20th century. The continuous and rapid modification of scientific principles, particularly in physics, has finally rendered untenable the thesis that science is a collection of affirmations which are true with certainty. This idea would force us, in fact, to consider every theory which has been superseded "unscientific." As long as it was a question of ideas that were centuries old, such a reclassification was accepted as appropriate, but with the new rhythm of scientific development the same criterion would force us to exclude from "science" every result that was not obtained in the last few years. This has seemed unacceptable to scientists, probably because it would force them to accept as inevitable the future recognition that their own results were "unscientific." It has become clear, in other words, that a good definition of "science" should permit one to consider "scientific" even affirmations which contradict each other, like the principles of classical mechanics and the principles of relativistic mechanics. On the other hand it is obvious that the utility of the term science consists in the possibility of distinguishing "scientific" knowledge from other kinds of knowledge, also valid to be sure, like prescientific technological knowledge, or our knowledge of history.

What distinguishes science from other forms of knowledge is certainly not, therefore, the absolute validity of scientific affirmations.

So what is science?

At first sight it could seem that one might respond to such a question using two different methods: either describing the characteristics of science as it took shape historically, or attacking the problem on a theoretical plane. A little more careful analysis shows, however, that each of these two methods

[24] Since UFO stands for Unidentified Flying Object, the word UFOlogy means more or less 'knowledge of unknown flying objects': this is a case of a 'science' whose content is empty by definition. Analogous considerations apply to parapsychology.

presupposes the other. You can't attack the problem of characterizing the "scientific method" without knowing the science which events have actually produced, that is, without knowing the history of science. On the other hand, it is obvious that no history of science is possible which is not based on a definition of science, even a tacit or unconscious one.

The only way to avoid this apparent vicious circle is probably to go in a spiral, alternating the two methods in such a way that they justify each other in turn.

Since this book aims to be essentially historical and not philosophical, and yet awareness is always preferable to its opposite, we will begin in this section by giving a definition of "science," seeking to illustrate it, but without discussing its validity. The definition simply has the purpose of defining the object of the next chapters, clarifying, in particular, the criterion of selection of the works which we shall consider "scientific." Once the definition has served its purpose, helping us to determine a relatively homogeneous corpus of works, we will be able to turn (in chapter 6) to the problem of characterizing science, asking ourselves about the origins and the characteristics of the Hellenistic scientific method as determined historically. It is my conviction that a better understanding of the method used by the ancient scientists is essential even for the history of modern science (as we will try to show in the last chapter) and could be an important element in the debate on contemporary science (this last subject going beyond the subject of this book).

To arrive at our (provisional) definition of "science", let us begin by noting that certain theories considered scientific by everyone, like thermodynamics, Euclidean geometry, or probability theory, share the following essential characteristics:

1. Their "scientific" affirmations are not about concrete objects, but rather about specifically theoretical entities.

Euclidean geometry, for example, is able to make affirmations about angles or line segments, and thermodynamics about the temperature or entropy of a system, but there do not exist in nature "angles", "line segments", "temperature", or "entropy".

2. The theory has a rigorously deductive structure; it is constituted, that is, out of a few fundamental pronouncements ("axioms", "postulates", or "principles") about the characteristics of its entities, and by a unitary and universally accepted method for deducing from these an unlimited number of consequences.

In other words, the theory furnishes general methods for solving an indeterminate number of problems. Such problems, describable within the scope of the theory, are really “exercises”: problems, that is, about which there is general agreement among the experts on the methods which can be used both to solve them and to check the correctness of the solutions. The fundamental methods are calculation and proof. The “truth” of “scientific” affirmations is in this sense guaranteed.

3. Applications to the real world are based on “rules of correspondence” between the entities of the theory and concrete objects.

The “rules of correspondence”, in contrast to the affirmations within the theory, come with no absolute guarantee. The fundamental method for checking the rules of correspondence, that is, the applicability of the theory, is the experimental method. The domain of applicability of the rules of correspondence is always limited, however.

Every theory with the three characteristics just given will be called a “scientific theory.” The same term will be used also for certain other theories, which we may call “of a higher order.” These are distinguished from those considered up to now in not having “rules of correspondence” which permit them to be applied to the real world. They are applicable only to other “scientific theories”. This is frequently the case in contemporary mathematics. Naturally this does not alter in any essential way the rapport between theory and reality (except perhaps in the consciousness of a few of those who, working at the higher levels, are able to forget about it), insofar as this rapport, even if it is indirect, is still guaranteed by the same mechanism which informs all theories.

By the “exact sciences” we will mean the set of “scientific theories.”

A simple criterion to check whether a theory is “scientific” is to verify whether it is possible to compile for it a manual of exercises; if this is not possible, it is certain that one is not dealing with a “scientific theory.”

The great utility of “exact science” consists in furnishing models of reality within which there exists a guaranteed method for distinguishing false affirmations from true ones. While the philosophy of nature failed in its objective to produce absolutely true pronouncements about the world, science succeeds in guaranteeing the “truth” of its own affirmations, at the expense however of limiting its scope to models. Of course such models permit one to describe and predict natural phenomena, transferring them to the theoretical level by the rules of correspondence, solving the “exercises” thus obtained, and transferring the solutions back to the real world. There is even another possibility, most interesting: that of moving freely within the theory, arriving at points where the rules of correspondence associate no concrete thing. At that point, having the theoretical model for it, one can often construct the corresponding reality, modifying the existing world. Thus "scientific theories", even if they originate as descriptions of natural phenomena, because they possess this possibility of self-extension by demonstrative methods, usually become models of sectors of technological activity. "Scientific technology", characterized by the real development of a projection effected within a scientific theory, appears thus to be intrinsically bound up with the same methodological structure as exact science, and cannot help but be born with it.

One of the objectives of this work is the attempt to verify the last affirmation (which is in open opposition to the commonplace that there were no technical applications of science in antiquity) by way of an analysis of Hellenistic science and technology. We will also seek to clarify all the methodological characteristics propounded up to this point by examining the first "scientific theories", which are precisely the Hellenistic ones.

All "scientific theories" have limited utility, since in general they can only be used as models of phenomena that are not too "far" from those which motivated them in the first place. Theories which turn out to be inadequate to describe a new phenomenon have to be replaced; they remain "scientific theories", however, based on our definition, and can continue to be used within the appropriate domain.

The structure of science is enriched by crosslinks of various kinds between theories which stabilize them; sometimes one succeeds in including another one; more often they have intersecting regions of applicability.

Two essential aspects of exact science, strictly connected with each other, are on the one hand their methodological unity, and on the other their extreme flexibility in considering new objects of study. Whether the study of a phenomenon is "scientific" does not depend on the type of phenomenon that it is, but rather on whether it is possible to use "scientific theories," a possibility which is historically determined. Thus, for example, the study of chemical reactions, which had been purely empirical for centuries, became an "exact science" as soon as it was possible to confront the problem with such methods, with the creation of the atomic theory.

The most significant divisions among the exact sciences are those which are based not on the phenomena studied, but on the theories, each of which is in general applicable to a vast array of phenomena which would appear unrelated in the absence of the theory.

By science we mean above all the "exact sciences." The "empirical sciences" do have something in common with the exact sciences, and are distinct from pre-scientific ways of knowing, above all in that their development is based on the method of experiment, and is the work of specialists whose efforts, distinct from philosophical speculation or the professions, aims purely at knowledge. One can speak of theories also in the case of the empirical sciences, insofar as these too are based on the elaboration of specific theoretical concepts, but these "empirical theories" do not satisfy the second of the properties which we have used to define "scientific theories", insofar as they lack the rigorously deductive structure which characterizes the exact sciences. The "empirical theories" cannot extend themselves by the method of proof, are only useful as models of a specific phenomenology, and do not produce results exportable to other domains. For this reason it is possible and appropriate to classify the "empirical sciences", unlike the exact sciences, by their concrete object of study.

The use of modern "scientific theories" as privileged points of reference, as if one were dealing with absolute truth, has often deprived the history of science of correct historical methodology, and has been especially misleading in the case of ancient science. This point can be better clarified with an example. Among the many citations possible we choose a passage from Max Jammer:

> "Even Archimedes, the founder of statics, does not offer the slightest contribution to the development of the concept of force. His treatment of mechanics is purely geometric."[25]

The statics of Archimedes is a "scientific theory" that is capable of solving essentially the same problems as modern statics, which was invented by translating the theory of Archimedes into Newtonian language, where the concept of force assumes a fundamental role. As is proved by the various formulations of mechanics which don't make use of it, the concept of force is not a necessity of nature. To judge it a limitation of the theory of Archimedes that it makes scant contribution to the development of the concept of force, as Jammer seems implicitly to suggest, is a little like judging it a limitation

[25] M. Jammer, *Concepts of Force. A study on the foundations of dynamics*, Harvard 1957.

of classical Greek that it made scant contribution to the development of the word 'horse'.[26]

If one conceives the history of science as the history of successive "acquisitions of truth" regarding natural phenomena directly, one could hardly fail to make the same choice as many historians, relegating innovations in science to the category of trivia; but if one conceives "scientific theories" as theoretical models of sectors of human activity, it is clear that their historical interest becomes fundamental. On the one hand their study can furnish precious information about those sectors of activity for which the models themselves were elaborated and used; on the other hand, one is dealing with cultural artifacts which can be placed in relation with the other aspects of the civilization which elaborated them.

The contextualization of scientific theories risks causing us to forget the specificity of scientific knowledge. This has been one of the results of a process probably initiated by Thomas S. Kuhn in his famous book,[27] leading to the complete relativism of many authors. Kuhn's book contains many of the ideas set out to this point, but uses a concept of 'paradigm' which is much broader than that of 'scientific theory', characterized by the three properties explained above. It follows that Kuhn accepts into the category of 'science' forms of knowledge like Pythagorean mathematics, Aristotelian physics, or various medieval theories that are excluded by the definition used here. The difference consists in the fact that a 'paradigm', like Aristotelian physics, not possessing a rigorously deductive structure, and therefore incapable of extending itself by the method of proof, may furnish a scheme useful for picturing the known reality,[28] but cannot be used to project a different reality. There is therefore no relationship between technology and 'science' in the very broad sense that Kuhn gives to this word. The problem of the birth of science cannot even be posed in Kuhn's terminology.

The definition of 'science' proposed here will appear to many to be too restrictive. There is no doubt that many important conceptual elaborations often called 'scientific' remain outside of it. The use of a restrictive definition of science does not at all negate the importance of other ways of knowing (in-

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[26]In the particular case under examination it should be noted besides that research into 'purely geometric' formulations of mechanics have been continual from Lagrange to Einstein, whose theory of general relativity reduces gravitational force to 'pure geometry.'

[27]T.S. Kuhn, *The Structure of Scientific Revolutions*, Chicago 1962.

[28]Directly perceptible 'physical' properties are described rather better by Aristotelian physics than by the science that came after.

cluding those used in this book, among others) but has the effect of focussing attention on a certain intellectual tool, which, as we will try to show, we have inherited from Hellenism, and which has been essential in the construction of what has come to be called “modern civilization.”

1.4 Was there ‘science’ in classical Greece?

The thesis that ‘science’, in the particular sense that we have given to this term, is a product of Hellenism, should not be understood, obviously, in the sense that no element of the ‘scientific’ method appeared before 323 B.C.E., the conventional date that, for our purposes, was perhaps too hastily adopted. Many characteristics of science already appear in the period immediately preceding, in particular in the developments of geometry and Greek astronomy in the course of the V and IV centuries. We will seek to show, however, that

– not just in the empires of antiquity, but not even in Greece of the V century B.C.E. or in the works of Plato or Aristotle was the method which we have called ‘scientific’ completely present;

– the ‘explosion’ of scientific theories occurred in the course of the III century B.C.E., and was an essential characteristic of Hellenistic civilization;

– if one wants to single out a turning point in the process of formation of the new method, the best candidate seems to be the formation of the Empire of Alexander.

The assertion that classical Greek culture did not produce ‘science’ calls for a bit more precision.

The comparison of modern scientific ideas and ancient ones is usually made between modern physics and, above all, the conceptions of the Greeks, presented as a development of thought that, beginning with the Ionian school, seems to be substantially complete with Aristotle. To put the comparison in these terms allows one to pay homage to “Greek thought”, of which we all recognize we are the heirs, maintaining at the same time an obvious implied attitude of benevolent superiority. A modern physicist, speaking of ‘atoms’, is often conscious of using a terminology introduced by Leucippus and Democritus almost two thousand years ago. He recognizes the merits of those ancient thinkers who, entirely without adequate experimental apparatus, and above all without our subtle conceptual tools, were still able to guess a theory that in some ways ‘anticipates’ the modern one; such a recognition is willingly conceded, since it permits one to show ones own humanistic culture, savoring at the same time an agreeable sensation of superiority, based on the conviction that the ancient 'atoms', being only a product of philosophical imagination, could have in reality very little in common with the homonymic object of modern physics. The debt explicitly acknowledged by modern science to that of antiquity lies in general, more or less, in its vocabulary. Even a highly cultured scientist like Heisenberg, in making a comparison between Greek thought and modern physics, after spending a great deal of time on the pre-Socratics (pages that are interesting, to be sure), jumps from Aristotle to modern science, without giving even one word to the development of ancient 'exact science', which essentially began with Euclid.[29]

From now on we will instead occupy ourselves with Hellenistic science, with only occasional reference to its precedents in the classical period. This choice is owing to the fact that these precedents do not form part of our subject. The atomic theory of Leucippus and Democritus, for example, certainly has enormous interest for the history of thought, but it does not resemble a scientific theory in the sense we have given to this expression in the preceding section, insofar as, on the basis of the existing fragments, we do not know of any theorems proved by these ancient atomists, nor do we know of any true experiments performed by them.

The following points should be underlined, however:

– the explanation of phenomena with theories having as objects unobservable entities, like the atoms of the theory of Leucippus and Democritus, is a step of enormous importance toward the construction of 'scientific theories';

– many other ideas which lead to science, whether Hellenistic or modern, originate in Greek thought of the classical period. This is the case with deterministic mechanics, which seems to originate with Leucippus,[30] or with the distinction between primary and secondary qualities, present in Democritus,[31] which will be an essential basis for the formulation of quantitative theories of phenomena like sound, color, or the chemical properties of matter;

– even a few more specific ideas often considered 'scientific' appear already in the thought of the so-called pre-Socratics.[32] For example, science owes to the ancient atomists not just the generic concept and the name of 'atom',

[29] W. Heisenberg, *Physics and Philosophy*, New York 1958.

[30] Leucippus in H. Diels, *Die Fragmente der Vorsokratiker*, Berlin 1903; VI edition, Kranz Walther ed., Berlin 1951-1952, 3 vols.; reprinted Zürich 1996.

[31] Democritus in H. Diels [see previous note].

[32] Among the philosophers whom historiography has traditionally included as pre-Socratics, we will be particularly interested in Democritus, who in reality outlived Socrates by several years.

but also ideas like the chaotic motion of atoms (an idea which, developed in the Hellenistic period and rediscovered in the modern epoch, was essential to the birth of the kinetic theory of gases[33]), or the idea of the existence of atomic hooks which can link to each other[34] : an image occasionally still used as a didactic illustration in chemistry texts.

To give another illustration, let us consider the 'experiment of the bucket'. In one of its forms one considers the observation that if a bucket full of water is set into rapid rotation in a vertical circle, the water does not fall out. If, instead, one makes the bucket rotate about its vertical symmetry axis, one observes that the surface of the water assumes a characteristic form, not flat. In both cases one can observe that the equilibrium configuration of the water contained in the bucket depends not just on its position with respect to the Earth, but also on its state of motion, and allows one therefore to give an absolute meaning to the assertion that the bucket is 'in motion' (at least motion in a circle). Observations of this type, which we describe today in terms of "centrifugal force", have certainly been important for the birth of dynamics; but this is not a case of real experimentation, only of qualitative observations; it is no wonder, therefore, that these precede the birth of the "scientific theories." Analogous observations must have been made even much earlier, but the first theoretical use of the "experiment of the bucket' seems to be documented by Empedocles.[35] 'Centrifugal force' was used in the cosmological domain by Anaxagoras, among others, who explained the origin of our world by the separation of different kinds of matter by means of centrifugation in an immense vortex.[36] The idea of vortices in a

[33]See for example Diogenes Laertius, *Vitae philosophorum*, IX, 31, where the idea is attributed to Leucippus. It would be interesting to know the origin of the conception of the chaotic motion of atoms. An remarkable step of Lucretius on the disordered motion of dust particles illuminated by sunbeams gives an indication of the kind of phenomenology which could have suggested the idea. Lucretius points to the disordered and extremely rapid motion of the atoms as the ultimate cause of the motion, gradually slower, of particles of larger dimensions. It is interesting to compare the lucid explanation of Lucretius with the vitalist explanation given in 1828, apropos of an analogous phenomenon, by the famous discoverer of Brownian motion. (R. Brown, in "Philosophical Magazine", 4, 1828),(R. Brown, in "Annalen der Physik und Chemie", 14, 1828)

[34]The existence of atoms with hooks had been affirmed by Democritus, as we know from the (lost) book of Aristotle *On Democritus*, a passage of which is reported by Simplicius (*In Aristotelis De caelo commentaria*)

[35]See Aristotle, *De caelo*, II, 13. Empedocles, according to Aristotle, had used the experiment of the bucket in some kind of argument about the immobility of the Earth.

[36]Anaxagoras in Diels, op. cit., par. 125.

cosmological context will also remain for a long time in the history of thought: the theory of the formation of the solar system of Kant and Laplace seems to be influenced by it.

To be clear, many of the ideas of pre-Socratic philosophers seem close to the later Hellenistic scientific method. In no case, however, in the whole classical period, can one document the use of complete hypothetical-deductive theories, or the use of experimental method.[37]

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

> If, then, [the force] A will move B in time T by the length L, half of A, that is E, will not move B in the time T nor in some part of T, by a part of the length L that is to the whole of L in the same proportion as the force A is to the force E; [...] if it were otherwise, one man alone could move a ship by as much as you would get numerically, dividing the force of those who drag it onto the shore and the distance they all drag it.[38]

Without reconstructing the entire reasoning of Aristotle, we are interested here in certain essential characteristics of the method by which he attacks the problem of motion, as he does other 'physical' questions. The problem of Aristotle is to determine the quantitative relation between force, time, and displacement. With 'scientific' method one can solve problems of this kind in only two ways: either assuming a given relation as an 'axiom' (and then the experimental method is essential to check whether the real phenomena for which one wants to construct the model behave effectively as one would predict, applying the 'rules of correspondence' to this axiom), or deducing the desired relation by the method of demonstration within a 'scientific theory'

[37]The story that Pythagoras did some acoustic experiments (particularly in regard to the pitch emitted by strings under variable tension) is very popular, but the oldest source known to us in which it appears dates from about 100 C.E. (Nichomacus of Gerasa, *Manual of Harmony*). The story is not very credible, not just for chronological reasons, and for the general tendency of neo-Pythagorists like Nichomacus to backdate all knowledge to Pythagoras, but also because the same experiments are attributed not to Pythagoras but to Pythagoreans by Plutarch (*De animae procreatione in Timaeo*, 1020F-1021A) and by Porphyry (*In Ptolemaei Harmonica*). Iamblichus repeats the story of Nichomacus (*Vita pythagorica*, 115-119), but in another place follows the version of Porphyry (*In Nicomachi Arithmeticam introductionem*, 121).

[38]Aristotle, *Physics*, VII, 5, 250a.

that already exists. Aristotle, instead, cannot use either demonstration or experiment, since he does not have, nor does he want to construct, a 'scientific theory.' The 'forces', 'times', and 'lengths' of which he speaks are not in fact entities within a theory, but are conceived by him as concrete objects, for which it is possible to comprehend the necessary reciprocal relationships by philosophical speculation.

He points to an empirical fact (the impossibility for one man alone to move a ship), but the decisive argument will be that the part of the force considered acts in a different way depending on whether it is isolated or whether it is part of a whole, because in the second case the part exists only 'potentially'. Pointing to an empirical fact is thus, in reality, essentially illustrative. One seeks to deduce quantitative assertions about particular physical phenomena directly from general philosophical principles, found by qualitative observations of nature.

The refutation of Aristotelian argumentation by Archimedes, according to a tradition referred to by Plutarch and by Proclus, was very persuasive. Archimedes seems to have designed, within his 'scientific theory' of mechanics, a device with which one man alone (himself or the king, Hieron II, depending on which version you read) could push a ship into the water which had been dragged up onto the shore in the port of Syracuse (according to Proclus the ship was a fully loaded trireme[39]). The machine effected exactly that division of the force which Aristotle had considered impossible, and which probably was unprecedented in its practical effect, in the particular case of the ship. It was a crystal clear way to prove the superiority of 'scientific' method, in the sense already explained, to natural philosophy. Instead of reflecting the world in philosophical speculation, the scientific method had made possible an innovation, designing a machine which removed the impossibility observed by Aristotle.

The methodological value of the demonstrative experiment described by Plutarch and Proclus, which emerges most clearly in the comparison with the passage from Aristotle, is naturally independent of whether Archimedes actually intended to refer to Aristotle explicitly,[40] and of the historical reality of the details referred to. The essential thing is that since we know that Archimedes had actually developed the possibility of designing machines with

[39]Proclus, *In primum Euclidis elementorum librum commentarii* (ed. G. Friedlein), 63. The same story is told by Plutarch in slightly different form (Plutarch, *Vita Marcelli*, XIV, 8).

[40]C. Mugler has argued that the reference to Aristotle is intentional.

large mechanical advantage, this is certainly not a legend born out of nothing. The story, insofar as it transmits to us an example of the real devices which the mechanics of Archimedes rendered possible, and as it attests to the broad interest in this new technology, is certainly credible.[41] As a rule however, the episode of the ship is narrated instead within the legendary/anecdotal description of Archimedes the personage, depriving it of its significance.

One reads that Greek scientists had developed statics but not dynamics. That is, they knew the conditions of equilibrium but not the laws of the motion of bodies. These assertions leave the impression that the ancient scientists, thanks to their 'contemplative' nature, enjoyed observing bodies in equilibrium, being careful that they not move. The episode of Archimedes who designed and used a machine with which he could haul a ship by himself does not square with this impression. In truth 'our' dynamics had not been developed in the III century B.C.E., but the quantitative theory which certainly had been developed, of machines like winches and gear trains ought to be considered a form of 'dynamics', since what is of interest is certainly not just the equilibrium of such machines. The idea that Archimedes had created statics but not dynamics has its origin in the fact that while our statics essentially coincides with that of Archimedes, one cannot say the same of dynamics. The 'mechanics' of Archimedes (that is, literally, his 'science of the machine') was however a 'scientific theory' that concerned itself both with equilibrium and with motion, even if, like all scientific theories, it was applicable only to a limited range of phenomena.

The situation was probably analogous to that of our thermodynamics of reversible transformations. Since we know how to define the 'thermodynamic state' of a system only when it is in equilibrium, we know how to study thermodynamic transformations only by approximating them as a succession of states of equilibrium. One studies in this way also thermodynamic cycles which are a model of what happens in an internal combustion engine; the model, within certain limits, is applicable, but that does not mean that our internal combustion engines remain fixed in equilibrium; and no one has ever suggested we call it 'thermostatics' when we study these 'evolutions through states of equilibrium.' Analogously the principal mechanical problem of the III century B.C.E. was the study of machines which, while performing work,

[41] The origin of this tradition was probably not an actual experimental demonstration, but the admiration aroused by the machine designed by Archimedes to launch the enormous ship *Syracusan* (see Ateneus, *Deipnosophistae*, V, 207b).

could be treated by supposing that the forces acting were at every moment 'almost in equilibrium'. This is the case with a crane which slowly lifts a weight. The problems involving mechanical systems of this sort (in particular the calculation of their 'mechanical advantage'[42]) can be solved using the mechanics of Archimedes. Our 'classical mechanics' is superior to that of Archimedes since, besides including it, it can be applied also in cases where that hypothesis does not hold. Such a difference is however of the same nature as that which renders it inferior, for example, to relativistic mechanics. The essential qualitative leap, from natural philosophy to science, is already completed in Archimedes. After this it is just a question of developing theories capable of furnishing models for ever more general classes of phenomena, but the trail has been blazed, as is proved by the fact that the various Hellenistic scientific theories, such as the theory of simple machines, hydrostatics, and geometrical optics, have been incorporated essentially unchanged into modern science. We will return to later developments of Hellenistic mechanics and its relation to Newtonian dynamics in chapters ten and eleven.

1.5 The origins of Hellenistic science

Why was 'science' born just with the rise of Hellenistic civilization, that is, with the conquests of Alexander the Great?

An important role was probably played by the new kind of relationship established between Greek civilization and the ancient civilizations of Mesopotamia and Egypt. The tradition of Greek culture in the classical period, which besides history, theater, political democracy, and the masterpieces of literature and art known to everyone, had created the natural philosophy that we have already indicated, was obviously essential. But what did the creators of this stupendous civilization have to learn from Egypt, for example? It is important to take account of the fact (long ignored) that in spite of all the triumphs of Greek civilization, the Greeks of the classical age were still inferior to the inhabitants of Egypt and Mesopotamia from the technological point of view. Let us read a few sentences of Charles Singer in the epilogue of the second volume of his History of Technology:

> "Whatever one's point of view on beauty and one's interest in the art, literature, ethics, and thought of Greece and of Rome,

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

> it is no longer possible to maintain that their technology was superior to that of the ancient empires. The curve of technological capacity tends to fall rather than rise with the coming of classical culture. To see this clearly it is enough to compare the specific chapters of the first volume with the corresponding chapters of the present volume [...] Greece and Rome based their power on the destruction of older civilizations. The rise of the Hellenic peoples and that of Rome was principally a victory of barbarians over an exhausted but ancient civilization."[43]

This passage is one conclusion of a work on the history of technology (very comprehensive) to which the greatest experts in the field have contributed, and which should therefore be considered with great attention. It is striking however to find Greece and Rome continually linked in a way that is indissoluble and automatic. It is not clear in what sense Greece would have destroyed more ancient civilizations, nor in what sense the Hellenic peoples could be considered *barbarous.* Besides, it is easy to document, as we shall see, that the level of technology went up in Egypt under the Ptolemies. Singer's conclusion appears to have been obtained by superposing three very different elements:

(a) the observation (very interesting, because it is drawn from an enormous work, considering the many particular technologies studied) that the technologies of the ancient empires were superior to that of classical Greece (the point that interests us) and to that of Rome;

(b) the observation (rather obvious) that Rome based its own power on the destruction of superior civilizations;

(c) the commonplace that Greece and Rome are to be associated uncritically as an indissoluble binary unity, and that 'Greek civilization' means essentially that of the classical period, forgetting the originality of Hellenistic civilization.

We can consider it certain in any case that the Greeks who went to Egypt and Mesopotamia in the time of Alexander's conquests found there a level of technology superior to their own. This fact is completely unsurprising, since in every case, whether it be classical Greece or Egypt and Mesopotamia, one is dealing with civilizations in which the development of technology happened by slow accumulation.[44] The Egyptian and Mesopotamian civilizations had

[43] C. Singer, et. al., it A History of Technology Oxford 1956, vol II, pp 766-767.

[44] Naturally the rate of technological development hasn't always been constant. There

thousands of years to accumulate empirical knowledge, write it down, and transmit it, giving them an insuperable advantage, unless there were a qualitative leap in methodology.

The traditions of the older civilizations, which had been in contact for centuries, had always attracted the interest of the Greeks. It is no accident that the beginning of Greek mathematics was attributed to Thales and Pythagoras, both of whom were said to have been in Egypt (and Pythagoras also in the East). But now the contact became much closer.[45] The Greeks who found themselves in the new kingdoms resulting from Alexander's conquests had to manage and understand economies and technologies more developed than what they were used to, with the essential guidance of their own superior rationality. In this circumstance science was born.

In reality it might seem that at the time of Alexander's empire many characteristics of scientific method had already been acquired. Since there does not remain to us a single scientific work of that period, it is difficult to affirm this with certainty, but the progress made by scientists like Eudoxus of Cnidos some ten years before the conquests of Alexander seems to have considerable continuity with the succeeding period. While indications of such continuity seem clear as regards isolated tools elaborated within mathematics or astronomy, however, the explosion of scientific method, consisting in the elaboration of many different scientific theories, understood as models of the real world based on systems of explicitly formulated assumptions, seems to be a novel characteristic of the Hellenistic period.

We note that the application of scientific method requires the capacity to use at the same time two different levels of discourse (one inside the scientific theory and the other regarding concrete objects) and to move from one level to the other by what we have called "rules of correspondence." One might conjecture that this capacity was favored in the territories belonging to Alexander's empire by the simultaneous presence of two cultures and by

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was a 'rapid' development in Mesopotamia, for example, particularly in the technologies of hydraulics, agriculture, and construction, in the epoch of the first urbanization, in the 4th millenium B.C.E. In this and analogous cases, though, one is thinking of 'rapid' development in a relative sense, in that it required many centuries. We will return to this point in section 7.2.

[45]It should be observed that the interaction between the Greeks and the territories of the ancient empires had intensified in the course of the 4th century, also thanks to mass immigration, and therefore the intensification of contacts of which we are speaking in some measure (difficult to make precise) preceded the enterprise of Alexander, and contributed to motivating it.

the ability developed by the Greek immigrants to use both simultaneously, each in its own proper domain, in particular framing in its own conceptual scheme each of the large number of empirical technologies handed down by Egyptian and Mesopotamian culture.[46]

An example of the capacity of Greek science to furnish a rational picture within which the knowledge of the ancient civilizations could be used and developed is offered by the organization, under the Ptolemies, of the works of hydraulic engineering for the regulation of the level of the Nile. This is a problem in which Egyptian civilization had accumulated thousands of years of experience; in fact it had been the problem which led to the very birth of Egypt as a unitary state.[47] The Ptolemies organized the works necessary using many Egyptian experts, but trusted the general direction of the field to Greek engineers. We will see further on what these Greek engineers were in a position to do.

[46] We note incidentally that an analogous contemporary use of two different cultures (that of the people themselves and that of the country in which they live) has been characteristic in the modern age of the Jews, to whom we also owe many of the principle results of modern science.

[47] According to an observation of Karl Marx, the Egyptian state, and the state structures of other ancient civilizations along rivers (Mesopotamia, the Indus Valley civilization, and the Yellow River civilization in China), originated in the need to coordinate works of irrigation and the construction of dikes. Such observations were the point of departure of Karl Wittfogel in his monumental studies of "Hydraulic civilization" and "hydraulic despotism". Apart from his treatment, which was strongly ideological, the essential role played by problems of water management in the process of formation of the state is today generally recognized. The fact that the Greeks, in just a few years, improved upon the more ancient "hydraulic civilization" in their works on hydraulics illustrates very well the power of the new scientific method.