Chapter 8
The Creation of Second-Order Knowledge in Ancient Greek Science as a Process in the Globalization of Knowledge

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Between 600 BCE and 200 CE Greek philosophers and scientists developed a number of second-order concepts that exerted a massive influence on the development of our modern global science. These include the notion of mathematical proof (exemplified by Euclid's *Elements*), geometrical models of the heavens with quantitative predictive power (Ptolemaic astronomy), and the idea that medical treatment must be based on an explanatory theory of the cause and cure of disease. The primary question addressed in this paper is this: in what sense can the creation of these concepts or "images of knowledge" (Elkana 1986) be viewed as part of a long-term process of the globalization of knowledge?

The ancient Greeks traced the origin of many aspects of their culture to the neighboring civilizations of Egypt and the Near East. Yet modern scholarship has often been reluctant to adopt such a perspective. That the Greeks had ample opportunity for contact with neighboring cultures in the Hellenistic period and thereafter is clear. In the aftermath of Alexander's conquests Greek culture became dominant across the Mediterranean world, even if the precise character and limits of Hellenization varied from place to place (Momigliano 1975). But the case for widespread cultural contact and its impact during the formative period of Greek culture has only recently begun to be made systematically on the basis of archaeological and linguistic evidence (Burkert 1992, 2004). The evidence for connections is early and extensive. In the eighth century BCE a most important instance of cultural diffusion took place when alphabetic writing, which had been developed in Phoenicia, was adapted to the Greek language. Motifs with close near Eastern parallels can be discerned in both the art and literature of the period. The migration of specialized practitioners or craftsmen supplies a plausible mechanism for much of this diffusion. The spread of techniques such as ivory carving and bronze working testifies to close apprenticeship between Greeks and eastern craftsmen (Burkert 1992, 22). Artistic representations and linguistic evidence both support the theory that divination spread from Mesopotamia to the West, presumably as a result of the migration of expert practitioners (Burkert 1992, 46–53).

The upshot of this work has been to change the terms of the debate: the burden of proof is now on those who would deny that contact with neighboring civilizations contributed in a significant way to the Greeks' distinctive cultural achievements. Yet it also raises a challenge to define more precisely the modalities of cultural influence, which have too often been conceived of as a matter of simple "borrowing" or "transmission." In examining the history of science it is also important to distinguish between different kinds of knowledge: to say that metalworking techniques spread from the Near East to the Greek world is one thing, but to claim that Euclidean geometry was adopted from Egypt quite another. In what follows I would like to offer a general characterization of the impact of cultural contact on the development of Greek science based on a distinction between two kinds of knowledge and two modes of cultural diffusion.

1. *First-order and second-order knowledge.* First-order knowledge is knowledge about the world, whether theoretical or practical in orientation; it may be a knowledge of how things are, or a knowledge of how to do or make things. By second-order knowledge I mean knowledge that derives from reflection on first-order knowledge: for example, a method for generating new procedures. Second-order knowledge is also an "image of knowledge" insofar as it sets out a conception or norm for what knowledge is in a particular domain. The idea of mathematical proof is a paradigmatic second-order concept, since it involves a specification of the conditions under which mathematical assertions can be accepted as true.
2. *Modes of diffusion.* I distinguish between diffusion through borrowing, in which a cultural product is transmitted from one culture to another more or less unchanged, and stimulus diffusion, in which the exposure to a product of one culture stimulates a parallel development in the other. As a modern example of the latter A. Kroeber, who coined the term "stimulus diffusion," cites the way in which the import of Chinese porcelain to Europe prompted Europeans to engage in a systematic search to find the materials and discover the procedures to replicate it (Kroeber 1940). In such a case there is clearly cultural influence, which may even be essential for the invention in the receiving culture: Europeans might never have had the idea to create porcelain, had they not seen the Chinese examples. But there is no simple transmission of knowledge.

My main argument is twofold: first, insofar as borrowing played a role in the development of Greek science it was generally limited to first-order knowledge; second, the notion of "stimulus diffusion" is helpful for understanding the development of second-order knowledge in Greek science. The spread of craft products and specialized practitioners tended to transmit first-order knowledge of methods and procedures, not second-order knowledge of how those methods were found. In that sense the Greek forms of second-order knowledge are distinctively Greek achievements. But the enrichment of first-order knowledge prompted by cultural contact contributed to their development in ways that may well have been essential to stimulating critical reflection. This is so in two ways: by augmenting the base of first-order knowledge, and by presenting specific examples or results that called out for explanation and reflection. As Aristotle observed, wonder is the origin of philosophy, and the Greeks certainly experienced wonder when confronted with the achievements of the much older civilizations of Egypt and Babylon (cf. Herodotus). Such wonder, I am suggesting, was an important factor in the development of second-order knowledge in Greek science.

Two preliminary points are crucial. First I do not claim that the Greeks *invented* second-order knowledge, or that the specifically Greek forms of second-order knowledge are the only such forms. Second-order knowledge can develop wherever there is substantial reflection on methods or procedures, and such reflection is present in many cultures and many contexts (Elkana 1986). My concern is with the development of specific kinds of systematic second-order reflection in the Greek context. Second, my reason for emphasizing these forms of second-order knowledge is their enormous influence on the subsequent development of science. I do not mean to suggest that the history of science is limited to a history of second-order knowledge, nor that these are the *only* forms of such knowledge that were influential.

With these points in mind I now turn to a brief examination of four related areas of Greek science in which contact with foreign cultures played an important role: cosmology, mathematics, medicine and astronomy. My discussion makes no claim to comprehensiveness. Its goal is the much more limited one of exploring how the distinctions I have set out above can provide a useful framework for analyzing the development of Greek science as a process in the globalization of knowledge.

8.1 Cosmology

By "cosmology" I mean a more or less systematic account of the structure of the world and the place of human beings in it. In this sense cosmological thought is a feature of the mythology and literature of almost all cultures, including of course ancient Mesopotamia and Egypt as well as Greece. But the type of cosmological thought that developed between the sixth and fourth centuries BCE in ancient Greek culture is quite different from what came before. Three features of these systems are important for present purposes.

1. First, these Greek cosmologies offer a certain kind of explanation of the universe. They typically seek to reduce the diversity of observable phenomena to the interaction of a small number of factors, which behave in consistent ways in a wide variety of contexts. And they are "rational" in the sense that they are supported by explicit reasons and arguments. For example, Anaximenes explains all physical transformations by condensation and rarefaction, and offers evidence (the behavior of breath exhaled from the mouth) that heating and cooling can be reduced to those processes.
2. Second, early Greek cosmologies typically envision the large-scale structure of the universe in terms of geometrical models with a high degree of sym-

metry. For example, Anaximander conceives of the sun, moon and stars as apertures in a set of concentric rings, which are supposed to explain phenomena such as eclipses and the phases of the moon.

3. Finally, analogies with various crafts are an important source of both the particular explanations and the geometrical models characteristic of this tradition. Thus Anaximander's cosmic rings are likened to wheels, while Anaximenes likens condensation and rarefaction to the production of felt from wool.

The earliest Greek cosmologies are an example of first-order knowledge; they attempt to set out images of the world rather than images of knowledge. Yet in their emphasis on systematic, reductive, and general explanation they represent a new kind of first-order knowledge that is quite different from anything to be found in ancient Mesopotamia or Egypt. Whatever parallels there may be between the cosmic geography in a Babylonian text and some Greek system are not as significant as the context in which such a system is embedded: they are, at most, a kind of "scaffolding" (Livingstone 1986; Burkert 1992, 66–69). As Rochberg writes:

> Mesopotamian cosmologies are reflected in texts whose goals were assuredly not to construct a definitive cosmic picture to serve as the framework for inquiry about natural phenomena. (Rochberg 1993, 51)

That, of course, is precisely what the Greeks *were* doing. Yet it is surely no accident that this particular tradition in Greek thought begins in Miletus, at the heart of the cultural crossroads that was Asia Minor in the sixth century BCE. Through Parmenides' critique in the early fifth century BCE Greek cosmological thought becomes second order, as explicit standards for the validity of cosmological accounts and arguments are developed and articulated. But this critique of course presupposes the existence of the earlier systems.

8.2 Mathematics

A distinctive achievement of early Greek mathematics is the development of the second-order concept of proof, which implies analysis of the conditions under which mathematical assertions can be accepted as true. While a concern with proof is the hallmark of Greek mathematics as represented by authors such as Euclid, Archimedes and Apollonius, it is not a feature of all Greek mathematical knowledge or even all Greek mathematical texts. Texts such as Heron of Alexandria's *Metrica* (probably first century CE) testify to another type of Greek mathematical knowledge, one concerned with practical problems of calculation and mensuration rather than deductive proof. Such texts may reflect the diffusion of much older techniques from the near East (Neugebauer 1957; Høyrup 1996). While there is very little direct evidence, knowledge of basic arithmetic and calculation techniques may well have spread to the early Greek world from the ancient near East (Waschkies 1989).

My main concern here is with the notion of mathematical proof as we find it in Euclid's *Elements*, which developed between the beginning of the sixth and end of the fourth centuries BCE. Since we have almost no Greek mathematical texts from this period, any reconstruction of these developments is unavoidably speculative. What we can do is compare the *Elements* itself with the extraordinarily rich sources for Babylonian mathematics that date from the third millennium BCE to the Seleucid period. Recent work has demonstrated the existence of significant second-order reflection and cognitive development over the course of this long tradition. In particular, the development of the sexagesimal system at the beginning of the second millennium opened up new conceptual possibilities that led to significant changes in mathematical practices (Damerow 2001). Though the texts' characteristic mode of presentation is that of problems to be solved, in many cases the "problems" considered do not correspond to any real-world situation, and are clearly generated by second-order reflection on the standard procedures. But it also seems clear that these developments were very different from those that took place in Greece; moreover the second-order reflection in the Babylonian tradition remained largely implicit in the written sources, making its transmission much more difficult.

The case of the Pythagorean theorem illustrates the problematic nature of any claim of a straightforward transmission of Babylonian mathematics to the Greeks. That the mathematicians of the Old Babylonian period "knew" the Pythagorean theorem is a widespread claim that goes back to the pioneering work of Otto Neugebauer in the early twentieth century; sometimes it is said that they "knew" the theorem but could not "prove" it. But on closer examination this apparently straightforward claim goes to the heart of the differences between Euclidean and Babylonian mathematics (Damerow 2001). While a number of early texts attest to the scribes' recognition that the Pythagorean relationship can be applied in the solution of certain problems, there is no evidence of any recognition that the relationship holds only under certain conditions (i.e. only for right-angled triangles). Rather, the necessity of the relationship within the Babylonian context follows from principles that are quite different from those that underlie Euclidean geometry. Moreover, a close analysis reveals that contexts in which it would be reasonable from the modern (and also Euclidean) perspective to infer that the scribes had knowledge of the theorem in its full generality can be explained in other ways (Damerow 2001). Similar observations apply *a fortiori* to the claim, widespread in mid-twentieth century scholarship, that the Babylonians developed a kind of algebra that was somehow transmitted to the Greeks and then reformulated in geometrical terms (the so-called "geometrical algebra" supposedly exemplified in Book 2 of the *Elements*). Recent work by Jens Høyrup has shown that much of Old Bablyonian mathematics can itself be characterized as a kind of "geometrical algebra" insofar as it relies on geometrical visualization to compute relationships between lines, widths and surfaces (Høyrup 2002). Diagrams played an important role in Babylonian mathematical practice, as even a cursory examination of the cuneiform literature shows. Yet the Babylonian and Greek traditions make use of diagrams in quite different ways, and a close comparison with Euclid reveals more differences than similarities. Whereas Babylonian mathematics is focused on measurement and calculation the Greek texts eschew any mention of numbers; and the inductive character of Babylonian mathematics, in which generalizations are inferred from the solutions to specific problems, is opposed to the Euclidean practice of inferring general conclusions from explicit axioms (Robson 2008, 274–284; Rudman 2010, 195–211). Aside from the general similarity of subject matter, there are few close affinities between the two traditions.

The factors that drove the development of the notion of proof in the Greek context seem to have been quite different from those which stimulated critical reflection in the Babylonian scribal schools. They include:

1. the development of new mathematical concepts including incommensurability, which both reflected and called for analysis of the conditions under which they held of mathematical objects;
2. the rapid increase in the number of mathematical results discovered by the investigation of such concepts;
3. the development of a new kind of notation in which letters of the alphabet are used to refer to geometrical entities in the diagrams;
4. the possible impact of an emerging concern with second-order knowledge in the cosmological tradition in the wake of the Parmenidean critique (Szabó 1978).

An additional factor *may* have been familiarity with some of the results of Babylonian mathematics as transmitted by practitioners. For example, a Babylonian school-text (BM 15285) contains a series of diagrams illustrating an argument strikingly similar to the famous passage on "doubling the square" in Plato's *Meno* (82–86) where Socrates leads a slave boy to recognize a special case of the Pythagorean theorem (Damerow 2001, 240–243). Mathematical knowledge as expressed in diagrams of this kind could have been transmitted relatively easily and might have stimulated the Greeks to develop their own accounts of the conditions under which such results could be said to hold. Still, it is important to note that no concrete evidence of such transmission is at hand, and the possibility of influence via stimulus diffusion remains entirely circumstantial.

8.3 Medicine

I shall concentrate here on early Greek medicine as represented in the texts of the Hippocratic Corpus, a collection of writings by various authors dating largely from the fifth and fourth centuries BCE. These texts vary widely in their approach to medical theory and practice. Some of them display a number of features in common with Mesopotamian and Egyptian medical texts in regard to both form and content. The treatise *On Diseases 2,* for example, consists of a catalog of diseases indicating the signs by which they can be recognized and the appropriate treatment. There are affinities between the therapies mentioned in Greek texts and earlier material (Goltz 1974; Geller 2010). Further affinities have been noted between Greek concepts such as "breath" and "phlegm" and Babylonian notions (Geller 2007), as well as between the Greek notion of "residues" and the pathological agents of Egyptian medicine (Steuer and Saunders 1959). Greek doctors travelled widely over the ancient Mediterranean world, with some (e.g., Democedes of Croton) ending up at the Persian court. Egypt is known as a land famous for drugs as early as Homer's *Odyssey.* There is thus no reason to reject the notion that the first-order knowledge base of Greek doctors was significantly enriched by contact with the medical traditions of the Near East and Egypt.

But we can also identify in the Hippocratic texts a concern with methodological reflection that is not present in the material from the neighboring cultures. In particular, the conception of medicine as a form of expertise (*technê*) that has a basis in explanatory theory is developed by some (though by no means all) of the Hippocratic writers. This development was a result of several interacting factors. The impulse toward highly reductive explanation that can be traced in early cosmological thought had its impact on medicine, as the cosmological theorists tended to speculate on the construction of the human body or the causes of health and disease. The impact of this approach can be detected in a variety of Hippocratic treatises, and prompted the development of new methodological theories drawing on medical experience (Schiefsky 2005). Within the medical tradition itself we can trace a rapid growth in the extent of first-order medical knowledge; this is exemplified by texts like the Hippocratic *Epidemics*, which contain case histories of disease collected by practitioners in their travels around the Greek world. The *Epidemics* testify to an ongoing engagement with the problem of relating general rules to particular cases, for as well as individual case histories they also contain an extensive body of prognostic and therapeutic generalizations that are closely related to the material in what is perhaps the most representative and influential Hippocratic text of all, the *Aphorisms.* The geographical range of the Greek doctors also prompted reflection on the conditions under which generalizations such as those expressed in the *Aphorisms* could be considered valid, for a rule that held under one set of climatic or geographical conditions might not hold elsewhere. The important early treatise *Airs, Waters, Places,* for example, sets out a general theory of the effects of environmental factors on human beings, and incorporates it into a wide-ranging ethnographic discussion of foreign lands and peoples. Similarly, the treatise *Prognostic* ends by saying that the prognostic "signs" it sets forth will be valid everywhere, not just in certain locales. Reflection on geographical variation and individual differences stimulated the development of general theories of the working of humoral factors such as phlegm and bile, which were supposed to explain the effects of the environment on all individuals *wherever* they might be located, and *whatever* their constitution might be.

Thus in medicine, as in mathematics, reflection on the conditions under which certain generalizations held stimulated the drive toward theoretical justification and the clarification of basic concepts. The Hippocratic texts themselves amply document this critical reflection, and there is no reason to think that it was the result of borrowing or transmission from Egypt or Mesopotamia. The major impact of the Greeks' longstanding contact with the medicine of those lands seems to have been an enrichment of the stock of first-order medical knowledge possessed by the Greek doctors: knowledge of therapies, procedures, techniques. This was by no means insignificant. Insofar as procedures worked, or were thought to work, they became a reliable starting point for reflecting on *why* they worked.

8.4 Astronomy

The crucial development is that of the astronomical model as a geometrical representation that can be matched to observational data so as to yield exact quantitative predictions. The development of the so-called "two-sphere" model, with the spherical earth inside a spherical heaven that rotates once a day, is securely attested by the middle of the fourth century BCE; this explained a wide variety of observations of the movement of the sun, moon and stars (Kuhn 1957). The precise stages of its development are obscure, but a plausible case can be made that reflection on the nature of technical instruments and procedures played an important role, as in other areas of early Greek cosmology (Szabó 1992). By the middle of the fourth century BCE, we have evidence of a geometrical model (Eudoxus' theory of concentric spheres) that was clearly intended to represent the more complex features of planetary motion. Though this was a remarkable display of geometrical ingenuity that provided a qualitative explanation of phenomena such as retrograde motion, it is unclear whether it was intended to yield exact quantitative predictions.

Mathematical modeling of planetary phenomena with the goal of exact prediction arose first in Babylon, and reached the pinnacle of its development during the Seleucid period (Neugebauer 1957). Instead of constructing geometrical models of the cosmos, the Babylonians used combinations of arithmetical sequences to model the recurrence of phenomena such as the beginning or end of a planet's retrograde motion. The Babylonian approach aims at determining the time of recurrence of these periodic phenomena, while the Greek geometrical models allow the determination of planetary longitudes at any given time. The sophisticated models of Seleucid-era Babylonian astronomy were clearly the fruit of much second-order reflection. Procedures had to be developed for the modification of arithmetical schemes to fit observational data; a key technique is the isolation of variation in one phenomenon so that the variation in another can be studied (Neugebauer 1945; Swerdlow 1998). But the second-order reflections associated with these developments are not expressed in the texts themselves. Indeed even the methods used to generate the predictions are not normally expressed; most of the texts are ephemerides from which the methods of computation (and *a fortiori* the general development of these methods) must be laboriously reconstructed. The scribes do not seem to have committed their methods to writing; nor did they record whatever ideas they may have had about the meaning or general significance of the periodicities that their work so accurately represented.

The spread of these Babylonian methods across the Greek-speaking Hellenistic world is the most well-documented and extensive case of the transmission of scientific knowledge in the ancient Mediterranean world. That Hipparchus in the second century BCE and Ptolemy in the second century CE used Babylonian parameters in constructing their geometrical models has long been recognized. But it is not just a question of adopting Babylonian parameters: Babylonian methods also spread across the Greek-speaking world to an extent that has only recently become clear (Jones 1991, 1996, 1999). Not only Hipparchus himself, but also pre-Ptolemaic writers such as Hypsicles and Geminus make use of Babylonian methods, often without drawing attention to their provenance (Evans 1998; Berggren and Evans 2006). A number of papyri from Greco-Roman Egypt indicate that practitioners of astronomy or astrology adopted the Babylonian methods for the purpose of prediction, though these texts testify to some significant adaptations of these methods as well as translation into the conceptual framework of the Greek geometrical tradition (Jones 1996, 1999). As usual, knowledge is transformed in the process of transmission.

The adaptation of Babylonian arithmetical methods alongside the Greek geometrical approach led to a methodological tension that was resolved only in the work of Ptolemy. The Babylonian methods yielded accurate prediction, but it was not at all clear why they did; unlike the Greek geometrical models, they did not have any obvious cosmological significance. While authors such as Hypsicles and Geminus do not seem to have perceived any tension in this situation, it is clearly present in Ptolemy, and was surely an important factor that prompted him to recast mathematical astronomy on strictly geometrical lines in the second century CE. His remarks in the *Almagest* on the inadequacy of all earlier attempts to offer theories of planetary motion are as much a criticism of the Babylonian or "Greco-Babylonian" approaches as they are a claim to his own original achievement (*Almagest* 9.2; cf. Neugebauer 1945). Ptolemy made use of Babylonian parameters, which were the essential foundation of a system with quantitative predictive power, but the diffusion of Babylonian methods stimulated him to develop his own strictly geometrical approach. The end result was the Ptolemaic system, a powerful fusion of highly accurate prediction with an overarching cosmological framework which, despite internal tensions, dominated astronomy in the Islamic and European Middle Ages down to Copernicus. Here, then, in the best-documented case of the diffusion of scientific knowledge that we have from antiquity, we find clear evidence both of the transmission of Babylonian methods to the Greek world, and of their role in stimulating the development of a distinctively Greek approach.

8.5 Conclusions

I hope that this survey, however brief and speculative, has at least succeeded in showing the usefulness of the concepts I have introduced for understanding the impact of Egypt and the Near East on the development of Greek science. Contact with these cultures enriched the first-order knowledge of the Greeks in all the fields we have discussed. Insofar as borrowing occurred it was largely restricted to such knowledge; in this way the knowledge traditions of Egypt and the Near East provided an important stimulus to critical reflection and the development of second-order knowledge. Finally, the material I have surveyed suggests that second-order knowledge tends not to be transmitted when it is not made explicit in written texts. Hence the influence of the distinctively Greek "images of knowledge" in the subsequent history of the globalization of knowledge is at least partly due to the large amount of methodological discussion that is characteristic of many Greek texts.

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