THE BEGINNINGS OF WESTERN SCIENCE

THE EUROPEAN SCIENTIFIC TRADITION IN PHILOSOPHICAL, RELIGIOUS, AND INSTITUTIONAL CONTEXT, 600 B.C. TO A.D. 1450

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Preface

The decades since World War II have seen an explosion of research on the history of ancient and medieval science. Much of this research is stunning in quality, and it has greatly enriched our understanding of early Western science. However, the broad synthetic and interpretive efforts needed to communicate the fruits of this research to a larger readership have been surprisingly meager. Indeed, while the curve of research publications continues to rise, the production of books broad in coverage and addressed to the general educated reader and scholars specializing in other fields seems to be declining.

A brief survey of the available literature on ancient and medieval science may help to make the point. The first substantial, knowledgeable, postwar account of ancient and medieval science appeared in a book by E. J. Dijksterhuis, published originally in Dutch as *Mechanisering van het Wereldbeeld* (1950), subsequently translated into English as *The Mechanization of the World Picture* (1961). By the time the English translation of Dijksterhuis became available, Alistair Crombie's *Augustine to Galileo* (1952) had already been around for nearly a decade, helping to fuel a growing sense of purpose and excitement among historians of medieval science. Perhaps Crombie's success frightened off the competition. Whatever the reason, nearly twenty years passed before the appearance of another synthetic work on medieval science: Edward Grant's brief *Physical Science in the Middle Ages* (1971), followed three years later by Olaf Pedersen and Mogens Pihl's *Early Physics and Astronomy: A Historical Introduction* (1974), both books restricted (as their titles indicate) to the physical sciences. Nothing has appeared since Pedersen and Pihl except the collection prepared under my editorship, *Science in the Middle Ages* (1978), which marshaled the talents of sixteen distinguished historians of medieval science to interpret the current state of the field for a relatively advanced audience. Although many of the essays contained in *Science in the Middle Ages* retain their authoritative status, the book as a whole suffers from a lack of unity, gaps in coverage, and (increasingly) old age.

The only books thus far mentioned that deal more than incidentally with ancient science are those of Dijksterhuis and of Pedersen and Pihl. For better or for worse, ancient science and medieval science have developed separate identities and separate interpretive literatures. Benjamin Farrington's *Greek Science* (two parts, published in 1944 and 1949, respectively) led the way on the history of Greek science. This was soon supplanted by the authoritative book of Marshall Clagett, *Greek Science in Antiquity* (1957). Giorgio de Santillana's *The Origins of Scientific Thought* followed in 1961. Roman science received separate treatment in William H. Stahl's *Roman Science* (1962). And in the early 70s G. E. R. Lloyd produced two widely praised volumes—*Early Greek Science: Thales to Aristotle* (1970) and *Greek Science after Aristotle* (1973)—which have held the field unchallenged for the past two decades.

Twenty years after Lloyd and forty years after Crombie (the last author to offer broad coverage of medieval science) does not seem too soon for a new attempt. The present book is a product of that conviction. I do not expect this book to replace its predecessors, particularly Lloyd's excellent volumes, but to achieve certain other goals. First, I have endeavored to take into account a considerable body of research that was not available to my predecessors. (For example, about two-thirds of the items in the bibliography at the back of this book were not available to Lloyd and Grant in the early 70s.) Second, by conjoining ancient and medieval science in a single volume, I have gained the opportunity to examine questions of continuity between ancient and medieval science in ways discouraged by separate treatment of the two halves, and also to raise problems of transmission that are otherwise apt to disappear into the crack.

Third, as the subtitle of this book is meant to suggest, I believe that I have more persistently attempted to place ancient and medieval science in philosophical, religious, and institutional (largely educational) context than have the authors of previous surveys. I am hardly the first to keep an eye on philosophical context. But I do not believe there is any other modern survey that has taken seriously the religious context and done so without embarrassment and without an apologetic or polemical agenda. If I have made any original contribution, this is probably where it lies.

My aim in this book is synthetic rather than encyclopedic. I endeavor to be broad in reach, confronting the major themes in the history of ancient and medieval science, while supplying enough reliable factual data to meet the needs of the reader who at the outset knows nothing about the subject. I have, of course, built on the accumulated scholarship of the past, but I have not hesitated to offer new interpretations and fresh judgments on old historical disputes. I have doubtless been more dependent on existing interpretive traditions for ancient science (where, in all honesty, I am an interested outsider) than for medieval science (my home ground). And, of course, I do not claim to have gotten all of it "right"—or even to have asked all of the right questions—on either the ancient or the medieval period; my hope is that this book will be received as a contribution to a continuing dialogue on the subjects it addresses.

I have written with a diverse audience in mind. Passages in which I lecture the reader on the proper ways of doing history and warn against a variety of perils (one reader of the manuscript has twitted me for the frequency of "anti-Whig inoculation") will be immediately recognizable as the products of long classroom experience; and it is my hope that this book will indeed prove suitable for classroom use. I am also hopeful that it will serve the general educated reader and historians who do not specialize in the history of ancient and medieval science.

Finally, two remarks about endnotes and bibliography. First, I have used the notes not only for purposes of documentation and acknowledgment of scholarly debt, but also as an opportunity for a running bibliographical commentary, in which I suggest sources (frequently at an advanced level) where the subject at hand may be fruitfully pursued. Second, in both the notes and the bibliography I have (with the student audience and the general reader in mind) heavily emphasized English-language literature. Sources in foreign languages are included only where it seems to me there is nothing comparable in English.

Nobody covers a subject as large as this one without a great deal of help, and I am profoundly indebted to friends and colleagues who have done their best to instruct me in the intricacies of their various specialties and rescue me from confusion and error. I have not always been an apt pupil, and some will still find in this book interpretations that they do not like.

Every chapter has been read and commented upon by colleagues knowledgeable in its subject matter. My greatest debt is to four people who read the manuscript from beginning to end and helped me to see its most glaring deficiencies: Michael H. Shank, Bruce S. Eastwood, Robert J. Richards, and Albert Van Helden. Others who read one or more chapters in their areas of expertise are: Thomas H. Broman, Frank M. Clover, Harold J. Cook, William J. Courtenay, Faye M. Getz, Owen Gingerich, Edward Grant, R.

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Stephen Humphreys, James Lattis, Fannie J. LeMoine, James Longrigg, Peter Losin, A. G. Molland, William R. Newman, Franz Rosenthal, A. I. Sabra, George Saliba, John Scarborough, Margaret Schabas, Nancy G. Siraisi, Peter Sobol, Edith D. Sylla, the late Victor E. Thoren, Sabetai Unguru, Heinrich von Staden, and David A. Woodward. The manuscript was evaluated for classroom use, or given actual test runs in the classroom, by several scholars; for their feedback, I wish to thank Edward B. Davis, Frederick Gregory, Edward J. Larson, Alan J. Rocke, and Peter Ramberg. For help in identifying and obtaining illustrations I am indebted to Bruce S. Eastwood, Owen Gingerich, Edward Grant, John E. Murdoch, and David A. Woodward. And for maps, I thank the University of Wisconsin Cartographic Laboratory. If this list is remarkable for its length, I can only explain that I needed all the help I could get.

The idea for this book emerged from discussions at the University of Florida in the spring of 1986 about a possible history of science textbook project; for inspiration and encouragement I would like to thank Frederick Gregory (the moving force behind the meeting) and other discussants, including William B. Ashworth, Richard Burkhardt, Thomas L. Hankins, and Frederic L. Holmes. The book was written during my term as director of the Institute for Research in the Humanities at the University of Wisconsin. It is unlikely that the project would have remained on course without the unfailing efficiency of my administrative assistant, Loretta Freiling, and the steadfast encouragement and support of colleagues in the Humanities Institute and the Department of the History of Science. The book was finished during a month's residency at the Bellagio Study and Conference Center of the Rockefeller Foundation; I am indebted to the foundation and to the directors of the Bellagio Center, Francis and Jackie Sutton, for providing an incomparable setting in which to reflect and write. And finally, I am deeply grateful for the forbearance of my wife, Greta, and my son, Erik, who served as unpaid consultants on prose style and know this book as a series of disconnected fragments, not in any particular sequence.

ONE
Science and Its Origins

WHAT IS SCIENCE?

The nature of science has been the subject of vigorous debate for centuries—a debate conducted by scientists, philosophers, historians, and other interested parties. Although no general consensus has emerged, several conceptions of science have attracted powerful support. (1) One view holds science to be the pattern of behavior by which humans have gained control over their environment. Science is thus associated with craft traditions and technology, and prehistoric people are regarded as having contributed to the growth of science when they learned how to work metals or engage in successful agriculture. (2) An alternative opinion *distinguishes* between science and technology, viewing science as a body of theoretical knowledge, technology as the application of theoretical knowledge to the solution of practical problems. On this view, the technology of automobile design and construction is to be distinguished from theoretical mechanics, aerodynamics, and the other theoretical disciplines that guide it; and only the theoretical disciplines are to count as "sciences."

Those who adopt this second approach, viewing science as theoretical knowledge, do not generally wish to concede that all theories (regardless of their character or content) are scientific; and for such people the task of definition has just begun. If they wish to exclude certain kinds of theories, they must propose criteria by which to judge one theory scientific and another unscientific. (3) It has become quite popular, therefore, to define science by the form of its statements—universal, law-like statements, preferably expressed in the language of mathematics. Thus Boyle's law (formulated by Robert Boyle in the seventeenth century) states that the pressure in a gas is inversely proportional to its volume if everything else remains constant. (4) If this seems too restrictive a criterion, science can be defined instead by its methodology. Science is thus associated with a particular set of procedures, usually experimental, for exploring nature's secrets and confirming or disconfirming theories about her behavior. A claim is therefore scientific if and only if it has an experimental foundation. (5) Such a definition, in turn, yields easily to attempts to define science by its epistemological status (that is, the kind of warrant its claims are held to possess) or even the tenacity with which its practitioners hold its doctrines. Thus Bertrand Russell has argued that "it is not *what* the man of science believes that distinguishes him, but *how* and *why* he believes it. His beliefs are tentative, not dogmatic; they are based on evidence, not on authority or intuition."[1] Science on this view is a privileged way of knowing and of justifying one's knowledge.

(6) In many contexts science is defined not by its methodology or epistemological status, but by its content. Science is thus a particular set of beliefs about nature—more or less the current teachings of physics, chemistry, biology, geology, and the like. By this test, belief in alchemy, astrology, and parapsychology is unscientific. (7) The terms "science" and "scientific" are often applied to any procedure or belief characterized by rigor, precision, or objectivity. Sherlock Holmes, according to this usage, adopted a scientific approach to the investigation of crime. (8) And finally, "science" and "scientific" are often simply employed as general terms of approval—epithets that we attach to whatever we wish to applaud.

What this brief and incomplete survey demonstrates is something that should perhaps have been obvious from the beginning—namely, that many words (including most of the interesting ones) have multiple meanings, varying with the particular context of usage. These meanings are sometimes mutually compatible and complementary, sometimes not. Moreover, it seems futile to attempt to eliminate diversity of usage. After all, language is not a set of rules grounded in the nature of the universe, but a set of conventions adopted by a group of people; and every meaning of the term "science" discussed above is a convention accepted by a sizable community, which is unlikely to relinquish its favored usage without a fight. Or to put the point in a slightly different way, lexicography must be pursued as a descriptive, rather than a prescriptive, art. We must acknowledge, therefore, that the term "science" has diverse meanings, each of them legitimate.

Even if we could find a definition of modern science that would satisfy everybody, the historian would still face a difficult problem. If the historian of science were to investigate past practices and beliefs only insofar as those practices and beliefs resemble modern science, the result would be

a distorted picture. Distortion would be inevitable because science has changed in content, form, method, and function; and therefore the historian would not be responding to the past as it existed, but looking at the past through a grid that does not exactly fit. If we wish to do justice to the historical enterprise, we must take the past for what it was. And that means that we must resist the temptation to scour the past for examples or precursors of modern science. We must respect the way earlier generations approached nature, acknowledging that although it may differ from the modern way, it is nonetheless of interest because it is part of our intellectual ancestry. This is the only suitable way of understanding how we became what we are. The historian, then, requires a very broad definition of "science"—one that will permit investigation of the vast range of practices and beliefs that lie behind, and help us to understand, the modern scientific enterprise. We need to be broad and inclusive, rather than narrow and exclusive; and we should expect that the farther back we go, the broader we will need to be.[2]

This admonition is particularly important for anybody embarking on a study of the ancient and medieval worlds. If we were to restrict our attention to anticipations of modern science, we would be focusing on a very narrow range of activity, no doubt distorting it in the process, and overlooking many of the very beliefs and practices of ancient and medieval culture that should be the object of our study—those that will help us to understand the development, much later, of modern science.

I will do my best to heed my own advice in the pages that follow, adopting a definition of science as broad as that of the historical actors whose intellectual efforts we are attempting to understand. This does not mean, of course, that all distinctions are forbidden. I will distinguish between the craft and theoretical sides of science—a distinction that many ancient and medieval scholars would themselves have insisted upon—and I will focus my attention on the latter.[3] The exclusion of technology and the crafts from this narrative is not meant as a commentary on their relative importance, but rather as an acknowledgment of the magnitude of the problems confronting the history of technology and its status as a distinct historical specialty having its own skilled practitioners. My concern will be with the beginnings of scientific *thought*, and that will prove quite a sufficient challenge.

A final word about terminology. Up to now I have consistently employed the term "science." The time has come, however, to introduce the alternative expressions "natural philosophy" and "philosophy of nature," which will also appear frequently in this book. Why are these new expressions needed, and what are they meant to convey? The term "science" has connotations, both ancient and modern, that differentiate it somewhat (and in some contexts) from the subjects to which our investigation is directed. The modern term has all of the ambiguity sketched above, and the ancient terms (*scientia* in latin, *epistēmē* in Greek) were applicable to any system of belief characterized by rigor and certainty, whether or not it had anything to do with nature. It was thus common in the Middle Ages to refer to theology as a science (*scientia*). This book will explore ancient and medieval attempts to investigate *nature,* and the least ambiguous name for that enterprise was and is "natural philosophy" or "philosophy of nature."

But it is important that we not construe the use of these latter expressions as a demotion of the medieval investigation of nature from "scientific" to some lesser status. We would do well to remember that natural philosophy was the intellectual venture to which so important a scientific luminary as Isaac Newton (late seventeenth century) assigned his own work, entitling his great book on mechanics and gravitational theory *The Mathematical Principles of Natural Philosophy*. Natural philosophy, the investigation of nature, was conceived by Newton, as by his ancient and medieval predecessors, to be an integral part of the larger philosophical exploration of the total reality that humans confront.

In this book I will employ a diverse vocabulary, making practical concessions to the heterogeneity of customary usage. I will make regular use of the expression "natural philosophy," either to denote the scientific enterprise as a whole or to signify its more philosophical side. The term "science" will also be employed, most often as a synonym for "natural philosophy," sometimes to designate the more technical aspects of natural philosophy, and occasionally simply because conventional usage calls for that term in a certain context. There will be ample talk simply of "philosophy," for there is no hope of understanding natural philosophy if we ignore the larger enterprise to which it belonged. And, of course, I will make frequent reference to the subdisciplines of natural philosophy, the specific sciences: mathematics, astronomy, physics, optics, medicine, natural history, and the like. Careful attention to context should make the meaning clear in every case.

PREHISTORIC ATTITUDES TOWARD NATURE

From the beginning, the survival of the human race has depended on its ability to cope with the natural environment. Prehistoric people developed

impressive technologies for obtaining the necessities of life. They learned how to make tools, start fires, obtain shelter, hunt, fish, and gather fruits and vegetables. Successful hunting and food-gathering (and, after about 7000 or 8000 B.C., settled agriculture) required a substantial knowledge of animal behavior and the characteristics of plants. At a more advanced level, prehistoric people learned to distinguish between poisonous and therapeutic herbs. They developed a variety of crafts, including pottery, weaving, and metalworking. By 3500 they had invented the wheel. They were aware of the seasons and perceived the connection between the seasons and certain celestial phenomena. In short, they knew a great deal about their environment.

But the word "know," seemingly so clear and simple, is almost as tricky as the term "science"; indeed, it brings us back to the distinction between technology and theoretical science, discussed above. It is one thing to know how to do things, another to know why they behave as they do. One can engage in successful and sophisticated carpentry, for example, without any theoretical knowledge of stresses in the timbers one employs. An electrician with only the most rudimentary knowledge of electrical theory can successfully wire a house. It is possible to differentiate between poisonous and therapeutic herbs without possessing any biochemical knowledge that would explain poisonous or therapeutic properties. The point is simply that practical rules of thumb can be effectively employed even in the face of total ignorance of the theoretical principles that lie behind them. You can have "know-how" without theoretical knowledge.

It should be clear, then, that in practical or technological terms, the knowledge of prehistoric humans was great and growing. But what about theoretical knowledge? What did prehistoric people "know" or believe about the origins of the world in which they lived, its nature, and the causes of its numerous and diverse phenomena? Did they have any awareness of general laws or principles that governed the particular case? Did they even ask such questions? We have very little evidence on the subject. Prehistoric culture is by definition oral culture; and oral cultures, as long as they remain exclusively oral, leave no written remains. However, an examination of the findings of anthropologists studying preliterate tribes in the nineteenth and twentieth centuries, along with careful attention to remnants of prehistoric thought carried over into the earliest written records, will allow us to formulate a few tentative generalizations.

Critical to the investigation of intellectual culture in a preliterate society is an understanding of the process of communication. In the absence of writing, the only form of verbal communication is the spoken word; and the only storehouses of knowledge are the memories of individual members of the community. The transmission of ideas and beliefs in such a culture occurs only in face-to-face encounter, through a process that has been characterized as "a long chain of interlocking conversations" between its members. The portion of these conversations considered important enough to remember and pass on to succeeding generations forms the basis of an oral tradition, which serves as the principal repository for the collective experience and the general beliefs, attitudes, and values of the community.[4]

There is an important feature of oral tradition that demands our attention—namely, its fluidity. Oral tradition is typically in a continuous state of evolution, as it absorbs new experiences and adjusts to new conditions and needs within the community. Now this fluidity of oral tradition would be extremely perplexing if the function of oral tradition were conceived to be the communication of abstract historical or scientific data—the oral equivalent of a historical archive or a scientific report. But an oral culture, lacking the ability to write, certainly cannot create archives or reports; indeed, an oral culture lacks even the *idea* of writing and must therefore lack even the *idea* of a historical archive or a scientific report.[5] The primary function of oral tradition is the very practical one of explaining, and thereby justifying, the present state and structure of the community, supplying the community with a continuously evolving "social charter." For example, an account of past events may be employed to legitimate current leadership roles, property rights, or the present distribution of privileges and obligations. And in order to serve this function effectively, oral tradition must be capable of adjusting itself fairly rapidly to changes in social structure.[6]

But here we are principally interested in the *content* of oral traditions, especially those portions of the content that deal with the nature of the universe—the portions, that is, which might be thought of as the ingredients of a worldview or a cosmology. Such ingredients exist within every oral tradition, but often beneath the surface, seldom articulated, and almost never assembled into a coherent whole. It follows that we must be extremely reluctant to articulate the worldview of preliterate people on their behalf, for this cannot be done without *our* supplying the elements of coherence and system, thereby distorting the very conceptions we are attempting to portray. We may, nonetheless, formulate certain conclusions about the ingredients or elements of worldview within preliterate oral traditions. (The conclusions that follow are based on a mixture of evidence from prehistoric cultures and contemporary preliterate societies and, unless there is explicit warning to the contrary, should be taken to apply to both settings.)

It is clear that preliterate people, no less than those of us who live in a modern scientific culture, have a need for explanatory principles capable of bringing order, unity, and especially meaning to the apparently random and chaotic flow of events. But we should not expect the explanatory principles accepted by preliterate people to resemble ours: lacking any conception of "laws of nature" or deterministic causal mechanisms, their ideas of causation extend well beyond the sort of mechanical or physical action acknowledged by modern science. It is natural that in the search for meaning they should proceed within the framework of their own experience, projecting human or biological traits onto objects and events that seem to us devoid not only of humanity but also of life. Thus the beginning of the universe is typically described in terms of birth, and cosmic events may be interpreted as the outcome of struggle between opposing forces, one good and the other evil. There is an inclination in preliterate cultures not only to personalize but also to individualize causes, to suppose that things happen as they do because they have been willed to do so. This tendency has been described by H. and H. A. Frankfort:

> Our view of causality . . . would not satisfy primitive man because of the impersonal character of its explanations. It would not satisfy him, moreover, because of its generality. We understand phenomena, not by what makes them peculiar, but by what makes them manifestations of general laws. But a general law cannot do justice to the individual character of each event. And the individual character of the event is precisely what early man experiences most strongly. We may explain that certain physiological processes cause a man's death. Primitive man asks: Why should *this* man die *thus* at *this* moment? We can only say that, given these conditions, death will always occur. He wants to find a cause as specific and individual as the event which it must explain. The event . . . is experienced in its complexity and individuality, and these are matched by equally individual causes.[7]

Oral traditions typically portray the universe as consisting of sky and earth, and perhaps also an underworld. An African myth describes the earth as a mat that has been unrolled but remains tilted, thereby explaining upstream and downstream—an illustration of the general tendency to describe the universe in terms of familiar objects and processes. Deity is an omnipresent reality within the world of oral traditions, though in general no clear distinction is drawn between the natural, the supernatural, and the human; the gods do not transcend the universe but are rooted in it and subject to its principles. Belief in the existence of ghosts of the dead, spirits, and a variety of invisible powers, which magical ritual allows one to control, is another universal feature of oral tradition. Reincarnation (the idea that after death the soul returns in another body, either human or animal) is widely believed in. Conceptions of space and time are not (like those of modern physics) abstract and mathematical, but are invested with meaning and value drawn from the experience of the community. For example the cardinal directions for a community whose existence is closely connected to a river might be "upstream" and "downstream," rather than north, south, east, and west. Some oral cultures have difficulty conceiving of more than a very shallow past: an African tribe, the Tio, for example, cannot situate anybody farther back in time than two generations.[8]

There is a strong tendency within oral traditions to identify causes with beginnings, so that to explain something is to identify its historical origins. Within such a conceptual framework, the distinction that we make between scientific and historical understanding cannot be sharply drawn and may be nonexistent. Thus when we look for the features of oral tradition that count for worldview or cosmology, they will almost always include an account of origins—the beginning of the world, the appearance of the first humans, the origin of animals, plants, and other important objects, and finally the formation of the community. Related to the account of origins is often a genealogy of gods, kings, or other heroic figures in the community's past, accompanied by stories about their heroic deeds. It is important to note that in such historical accounts the past is portrayed not as a chain of causes and effects that produce gradual change, but as a series of decisive, isolated events, by which the present order came into existence.[9]

These tendencies can be illustrated with examples from both ancient and contemporary oral cultures. According to the twentieth-century Kuba of equatorial Africa,

> Mboom or the original water had nine children, all called Woot, who in turn created the world. They were, apparently in order of appearance: Woot the ocean; Woot the digger, who dug riverbeds and trenches and threw up hills; Woot the flowing, who made rivers flow; Woot who created the woods and savannas; Woot who created the leaves; Woot who created the stones; Woot the sculptor, who made people out of wooden balls; Woot the inventor of prickly things such as fish, thorns, and paddles; and Woot the sharpener, who first gave an edge to pointed things. Death came to the world when a quarrel between the last two Woots led to the demise of one of them by the use of a sharpened point.[10]

Notice how this tale not only accounts for the origin of the human race and the major topographical features of the Kuba world, but also explains the invention of what the Kuba clearly considered a critically important tool—the sharpened object.

Similar themes abound in early Egyptian and Babylonian creation myths. According to one Egyptian account, in the beginning the sun-god, Atum, spat out Shu, the god of air, and Tefnut, the goddess of moisture. Thereafter,

> Shu and Tefnut, air and moisture, gave birth to earth and sky, the earth-god Geb and the sky-goddess Nut. . . . Then in their turn Geb and Nut, earth and sky, mated and produced two couples, the god Osiris and his consort Isis, the god Seth and his consort Nephthys. These represent the creatures of this world, whether human, divine, or cosmic.[11]

A Babylonian myth attributes the origin of the world to the sexual activity of Enki, god of the waters. Enki impregnated the goddess of the earth or soil, Ninhursag. This union of water and earth gave rise to vegetation, represented by the birth of the goddess of plants, Ninsar. Enki subsequently mated first with his daughter, then with his granddaughter, to produce various specific plants and plant products. Ninhursag, angered when Enki devoured eight of the new plants before she had the opportunity to name them, pronounced a curse on him. Fearing the consequences of Enki's demise (apparently the drying up of the waters), the other gods prevailed on Ninhursag to withdraw the curse and heal Enki of the various ailments induced by the curse, which she did by giving birth to eight healing deities, each associated with a part of the body—thus accounting for the origin of the healing arts.[12]

It will be convenient to pause for a moment on the healing arts, which can serve to illustrate some of the characteristics of oral cultures. There can be no doubt that healing practices were extremely important in ancient oral cultures, where primitive conditions made disease and injury everyday realities.[13] Minor medical problems, such as wounds and lesions, were no doubt treated by family members. More dramatic ailments—

major wounds, broken bones, severe and unexpected illness—might require assistance from somebody with more advanced knowledge and skill. A certain amount of medical specialization thus came into existence: some members of the tribe or the village became known for their herb-gathering ability, their proficiency in the setting of bones or the treatment of wounds, or their experience in assisting at childbirth.

But so described, the primitive medicine practiced in preliterate societies sounds remarkably like a rudimentary version of modern medicine. A more careful look reveals the healing arts within oral cultures to be inseparable and indistinguishable from religion and magic. The wise woman or the "medicine man" was valued not simply for pharmaceutical or surgical skill, but also for knowledge of the divine and demonic causes of disease and the magical and religious rituals by which it could be treated. If the problem was a splinter, a wound, a familiar rash, a digestive complaint, or a broken bone, the healer responded in the obvious way—by removing the splinter, binding the wound, applying a substance (if one were known) that would counteract the rash, issuing dietary prohibitions, and setting and splinting the broken limb. But if a family member became mysteriously and gravely ill, one might suspect sorcery or invasion of the body by an alien spirit. In such cases, more dramatic remedies would be called for—exorcism, divination, purification, songs, incantations, and other ritualistic activities.

There is one last feature of belief in oral cultures (both ancient and contemporary) that demands our attention—namely, the simultaneous acceptance of what seem to us incompatible alternatives, without any apparent awareness that such behavior could present a problem. Examples are innumerable, but it may suffice to note that the story of the nine Woots related above is one of seven (or more) myths of origin that circulate among the Kuba, while the Egyptians had a variety of alternatives to the story of Atum, Shu, Tefnut, and their offspring; and nobody seems (or seemed) to notice, or else to care, that all of them could not be true. Add to this the seemingly "fanciful" nature of many of the beliefs described above, and we inevitably raise the question of "primitive mentality": do the members of preliterate societies possess a mentality that is prelogical or mystical or in some other way different from our own; and, if so, exactly how is this mentality to be described and explained?[14]

This is an extremely complex and difficult problem, which has been hotly debated by anthropologists and others for the better part of the twentieth century, and I am not likely to resolve it here. But I can at least offer a word of methodological advice: namely, that it is wasted effort, contributing absolutely nothing to the cause of understanding, to spend time wishing that preliterate people would employ (or had employed) a conception and criteria of knowledge that they have (or had) never encountered—a conception, in the case of prehistoric people, that was not invented until centuries later. We make no progress by assuming that preliterate people were trying, but failing, to live up to our conceptions of knowledge and truth. It requires only a moment of reflection to realize that they must have been operating within quite a different linguistic and conceptual world, and with different purposes; and it is in the light of these that their achievements must be judged.

The stories embodied in oral traditions are intended to convey and reinforce the values and attitudes of the community, to offer satisfying explanations of the major features of the world as experienced by the community, and to legitimate the current social structure; stories enter the oral tradition (the collective memory) because of their effectiveness in achieving those ends, and as long as they continue to do so there is no reason to question them. There are no rewards for skepticism in such a social setting and few resources to facilitate challenge. Indeed, our highly developed conceptions of truth and the criteria that a claim must satisfy in order to be judged true (internal coherence, for example, or correspondence with an external reality) do not generally exist in oral cultures and, if explained to a member of an oral culture, would probably seem quite useless. Rather, the operative principle among preliterates is that of sanctioned belief—the sanction in question emerging from community consensus.[15]

Finally, if we are to understand the development of science in antiquity and the Middle Ages, we must ask how the preliterate patterns of belief that we have been examining yielded to, or were supplemented by, a new conception of knowledge and truth (represented most clearly in the principles of Aristotelian logic and the philosophical tradition it spawned). The decisive development seems to have been the invention of writing, which occurred in a series of steps. First there were pictographs, in which the written sign stood for the object itself. Around 3000 B.C. a system of word signs (or logograms) appeared, in which signs were created for the important words, as in Egyptian hieroglyphics. But in hieroglyphic writing, signs could also stand for sounds or syllables—the beginnings of syllabic writing. The development of fully syllabic systems about 1500 B.C. (that is, systems in which all nonsyllabic signs were discarded) made it possible and, indeed, reasonably easy for people to write down everything they could say. And finally fully alphabetic writing, which has a sign for each sound (both consonants and vowels), made its appearance in Greece about 800 B.C. and became widely disseminated in Greek culture in the sixth and fifth centuries.[16]

One of the critical contributions of writing, especially alphabetic writing, was to provide a means for the recording of oral traditions, thereby freezing what had hitherto been fluid, translating fleeting audible signals into enduring visible objects.[17] Writing thus served a storage function, replacing memory as the principal repository of knowledge. This had the revolutionary effect of opening knowledge claims to the possibility of inspection, comparison, and criticism. Presented with a written account of events, we can compare it with other (including older) written accounts of the same events, to a degree unthinkable within an exclusively oral culture. Such comparison encourages skepticism and, in antiquity, helped to create the distinction between truth, on the one hand, and myth or legend, on the other; that distinction, in turn, called for the formulation of criteria by which truthfulness could be ascertained; and out of the effort to formulate suitable criteria emerged rules of reasoning, which offered a foundation for serious philosophical activity.[18]

But giving permanent form to the spoken word does not merely encourage inspection and criticism. It also makes possible new kinds of intellectual activity that have no counterparts (or only weak ones) in an oral culture. Jack Goody has argued convincingly that early literate cultures produced large quantities of written inventories and other kinds of lists (mostly for administrative purposes), far more elaborate than anything an oral culture could conceivably produce; and, moreover, that these lists made possible new kinds of inspection and called for new thought processes or new ways of organizing thoughts. For one thing, the items in a list are removed from the context that gives them meaning in the world of oral discourse, and in that sense they have become abstractions. And in this abstract form they can be separated, sorted, and classified according to a variety of criteria, thereby giving rise to innumerable questions not likely to be raised in an oral culture. To give a single example, the lists of precise celestial observations assembled by early Babylonians could never have been collected and transmitted in oral form; their existence in writing, which allowed them to be minutely examined and compared, made possible the discovery of intricate patterns in the motions of the celestial bodies which we associate with the beginnings of mathematical astronomy and astrology.[19]

Two conclusions may be drawn from this argument. First, the invention of writing was a prerequisite for the development of philosophy and science in the ancient world. Second, the degree to which philosophy and

science flourished in the ancient world was, to a very significant degree, a function of the efficiency of the system of writing (alphabetic writing having a great advantage over all of the alternatives) and the breadth of its diffusion among the people. We see the earliest benefits of the use of word signs or logograms in Egypt and Mesopotamia, beginning about 3000 B.C. However, the difficulty and inefficiency of logographic writing inevitably limited its diffusion and made it the property of a small scholarly elite. In sixth- and fifth-century Greece, by contrast, the wide dissemination of alphabetic writing contributed to the spectacular development of philosophy and science. We must not imagine that literacy was sufficient of itself to produce the "Greek miracle" of the sixth and fifth centuries; other factors no doubt contributed, including prosperity, new principles of social and political organization, contact with Eastern cultures, and the introduction of a competitive style into Greek intellectual life. But surely the most important element in the mix was the emergence of Greece as the world's first widely literate culture.[20]

THE BEGINNINGS OF SCIENCE IN EGYPT AND MESOPOTAMIA

I will turn to the Greek world in the next chapter. Before doing so, I must touch briefly on pre-Greek developments in Egypt and Mesopotamia (the region between the Tigris and Euphrates rivers, site of ancient Babylonia and Assyria and of modern Iraq—see map 2). I have said enough about creation myths in the preceding section to reveal key features of Egyptian and Mesopotamian cosmological and cosmogonical speculation. Here I will restrict myself to the Egyptian and Mesopotamian contribution to several other subjects or disciplines that subsequently found a place within Greek and medieval European science: mathematics, astronomy, and medicine. The evidence is scanty but sufficient to convey a general picture.

The Greeks themselves believed that mathematics originated in Egypt and Mesopotamia. Herodotus (fifth century B.C.) reported that Pythagoras traveled to Egypt, where he was introduced by priests to the mysteries of Egyptian mathematics. From there, according to ancient tradition, he was carried captive to Babylon, where he came into contact with Babylonian mathematics. Eventually he made his way home to the island of Samos, bearing Egyptian and Babylonian mathematical treasure to the Greeks. Whether this and similar tales regarding other mathematicians are historically accurate or legendary is less important than the larger truth they convey—namely, that the Greeks were (and knew they were) the recipients of Egyptian and Babylonian mathematical knowledge.

By 3000 about B.C., the Egyptians developed a number system that was decimal in character, employing a different symbol for each power of 10 (1, 10, 100, and so forth). These symbols could be lined up, as in Roman numerals, to form any desired number. Thus if I represented 1, and ∩ represented 10, then the number 34 could be expressed as IIII∩∩∩. By about 1800 B.C. additional symbols had been devised for other numbers, so that, for example, 7 could be represented by a sickle (ʔ) rather than by seven vertical strokes. Addition and subtraction were simple operations in Egyptian arithmetic, performed as with Roman numerals, but multiplication and division were extremely clumsy; and the generalized concept of a fraction was unknown, the general rule allowing only unit fractions (fractions with a numerator of 1). Elementary problems of the following type could be solved: if one-seventh of a quantity is added to the quantity, and the sum equals 16, how large is the quantity?[21]

Egyptian geometrical knowledge seems to have been oriented toward practical problems, perhaps those of surveyors and builders. Egyptians were able to calculate the areas of simple plane figures, such as the triangle and the rectangle, and the volumes of simple solids, such as the pyramid. For example, to find the area of a triangle they took one-half the length of the base times the altitude; and, to find the volume of a pyramid, one-third the area of the base times the altitude. For calculating the area of a circle, the Egyptians worked out rules that correspond to a value for π of about 3.17. Finally, in one of the most obvious areas of applied mathematics, the Egyptians devised an official calendar consisting of twelve months of thirty days each, plus an additional five days at the end of the year—a calendar substantially simpler, because of its fixed character, than contemporary Babylonian calendars and those of the early Greek city-states, which attempted to take into account the lunar, as well as the solar, cycle.[22]

The contemporary mathematical achievement in Mesopotamia was an order of magnitude superior to that of the Egyptians. Clay tablets (see fig. 1.1) recovered in large quantities reveal a Babylonian number system, fully developed by about 2000 B.C., that was simultaneously decimal (based on the number 10) and sexagesimal (based on the number 60). We retain sexagesimal numbers today in our system for measuring time (sixty minutes to an hour) and angles (sixty minutes in a degree and 360 degrees in a circle). The Babylonians had separate symbols for 1 (▼) and 10 (◀); these could be combined like Roman numerals to form numbers up to 59. The number 32, for example, would be expressed by three of the tens symbol plus two of the units symbol, as in table 1.1.

But beyond 59 an important difference appears. Instead of forming the

Fig. 1.1. A Babylonian clay tablet (ca. 1900–1600 B.C.), containing a mathematical problem text dealing with bricks, their volumes, and their coverage. Yale Babylonian Collection, YBC 4607. The text is translated and discussed in O. Neugebauer and A. Sachs, eds., *Mathematical Cuneiform Texts*, pp. 91–97.

Table 1.1. Five Babylonian Sexagesimal Numbers and Their Hindu-Arabic equivalents.

	60^3	60^2	60	1	1/60	$1/60^2$	Modern Hindu-Arabic Equivalent
(1)				◀◀◀▼▼			32
(2)			▼▼	◀▼▼▼▼▼▼			2×60 + 16 = 136
(3)		▼	◀▼▼	◀◀▼▼▼			1×3600 + 12×60 + 23 = 4,343
(4)	▼▼	◀◀▼▼					2×216000 + 22 × 3600 = 511,200
(5)					◀◀	◀▼▼	2×1/60 + 12×1/3600 = 1/30 + 1/300 = 11/300

▼ = 1 ◀ = 10

number 60 by lining up six symbols for 10, the Babylonians used a place system similar to our own. In our number 234, the numeral 4 (situated in the "units column") signifies simply the number 4; the numeral 3, situated in the tens column represents the number 30; while the numeral 2, situated in the hundreds column stands for the number 200. Thus 234 is 200 + 30 + 4. The Babylonian place system worked similarly, except that successive columns represent powers of 60 rather than powers of 10. Thus in the second example in table 1.1, the two unit symbols in the sixties column represent not 2, but $2\times60=120$; and in the third example the unit symbol in the 60^2 column represents not 1 but $1\times60^2=3{,}600$. There was no equivalent of the decimal point by which to locate the units column, and this information would therefore have to be inferred from context. Multiplication tablets, tables of reciprocals, and tables of powers and roots were used to facilitate calculation. One of the great advantages of the sexagesimal system was the ease with which calculations could be performed using fractions.[23]

The full superiority of Babylonian mathematics over its Egyptian counterpart is evident when we turn to more difficult problems, which *we* would solve algebraically. Historians of mathematics sometimes refer to these problems as "algebra," useful shorthand for this aspect of the Babylonian mathematical enterprise, perhaps, but dangerous if it is taken to mean that they practiced genuine algebra—that is, that they had a generalized algebraic notation or an understanding of what we consider algebraic rules. What we can safely say is that Babylonian mathematicians used arithmetical operations to solve problems for which *we* would employ a quadratic equation. For example, we find many Babylonian tablets, including teaching texts, demonstrating how to solve problems such as the following: given the product of two numbers and their sum or difference, find the two numbers.[24]

One of the areas to which Babylonians applied their mathematical techniques was astronomy. The stars have been objects of investigation and speculation since earliest times. Some of our oldest written records, going back more than 4,000 years, are astronomical in character. There were several reasons for this interest in the heavens. One was agricultural, for it was obvious even from fairly casual observation that the agricultural seasons—the times for planting and harvesting—correspond to the motion of the sun and the position of certain stars and constellations in relation to the sun. A second reason was religious, for the heavens, especially the sun and moon, were usually associated with divinity. A third was astrological. And a fourth was calendric.

Some of the earliest effort was devoted to mapping the heavens—identifying and naming prominent stars and constellations, observing their relationships, and linking their visibility to the seasons. In Mesopotamia, systematic astronomical observation came to be practiced in the temples, for religious, astrological, and calendric purposes. Temple priests not only mapped the fixed stars but also identified the "wandering stars" or planets—the planets now named Mercury, Venus, Mars, Jupiter, and Saturn. (The sun and moon were also considered planets, because they too moved in relation to the fixed stars.) These seven planets were observed to move slowly through the heavens within the narrow band of the zodiac. By about 500 B.C. Babylonian priests had defined this band and identified the constellations that mark it off into twelve segments of thirty degrees each, thus giving us the signs of the zodiac. Once defined, the zodiac could function as a handy measuring system for charting the exact motions of the sun, moon, and remaining planets, and as a source of astrological predictions.[25]

The astrological aspect of Babylonian astronomy requires brief mention (on astrology, see also below, chap. 11). It is clear that astrological needs were a major motivation for the development of Babylonian mathematical astronomy. Out of astral religion—the association of the stars (specifically the wandering stars) with the gods—and the obvious fact that celestial events were connected with the seasons and the weather, there developed a system of judicial astrology, the attempt to make short-term predictions affecting the king and the kingdom on the basis of the current celestial configuration. It is also possible that horoscopic astrology, which predicts the course of a person's life from the celestial configuration at the time of birth, developed in the late Babylonian period. What is important is that both kinds of astrology called for detailed knowledge of solar, lunar, and the other planetary motions. Babylonian astrology was transmitted to the Greeks, who further developed it and passed it on to the Middle Ages, the early modern period, and ultimately the twentieth century. Through most of that long history, it should be noted, the astronomical and astrological traditions have been intimately linked.[26]

We do not have space to examine the development of Babylonian mathematical astronomy in detail. What is important is that in the period 500–300 B.C., the Babylonian astronomer-priest developed his art to the point where he could manipulate large quantities of astronomical data and make a variety of astronomical predictions. He had numerical models, in the form of arithmetic progressions, that enabled him to chart the daily motions of the sun and moon through the zodiac. From such data he could predict the first appearance of the new moon (important for the calendar, since the new moon signified the beginning of a new month); he could also predict lunar eclipses and the possibility or impossibility of solar eclipses. We must stress that he did this not by the use of geometrical models, as Greek astronomers would do, but simply through the use of numerical methods that extrapolated past observations into the future.[27]

The final area of Egyptian and Mesopotamian achievement to be considered is medical. A number of Egyptian medical papyri (written in the period 2500–1200 B.C.) have survived, and these offer us a fragmentary picture of the healing arts in ancient Egypt. From several of the papyri it becomes clear that a principal cause of disease was thought to be invasion of the body by evil forces or spirits. Relief was to be gained through rituals designed to appease or frighten the spirits—exorcism, incantation, purification, or the wearing of an appropriate amulet. The gods could be appealed to for protection: a prayer to the god Horus, found in the Leyden papyrus, reads in part, "Hail to thee, Horus . . . . I come to thee, I praise thy beauty: destroy thou the evil that is in my limbs."[28] Certain gods came especially to be associated with healing functions or healing cults: Thoth, Horus, Isis, and Imhotep. The view that each bodily organ was ruled by a specific god, who could be invoked for healing of that organ, seems to have been widespread. And all of this ritual, of course, required the assistance of an expert who was of acknowledged purity, who knew the required incantations, and who could assure that the ritual was properly performed to the smallest detail; this was the priest-healer.

Healing therapies in ancient Egypt were not limited to prayer, incantation, and ritual. Pharmacological remedies, prepared from animal, vegetable, or mineral substances, were also widespread—though their effectiveness was believed to be conditional on having been prepared and administered under appropriate ritual conditions. The Ebers papyrus (written about 1600 B.C., but containing material copied from much older texts) contains medical recipes for dealing with diseases of the skin, eyes, mouth, extremities, digestive and reproductive systems, and other internal organs; for treating wounds, burns, abscesses, ulcers, tumors, headaches, swollen glands, and bad breath.[29]

Surgery is dealt with in another papyrus, known as the Edwin Smith papyrus (written about the same time as the Ebers papyrus), which contains a surgical manual that systematically describes the treatment of wounds, fractures, and dislocations (see fig. 1.2).[30] One of the notable features of the Ebers and Edwin Smith papyri is the careful arrangement of case studies, beginning with a description of the problem and proceeding to diagnosis, verdict (as to whether or not the ailment is treatable), and treatment.

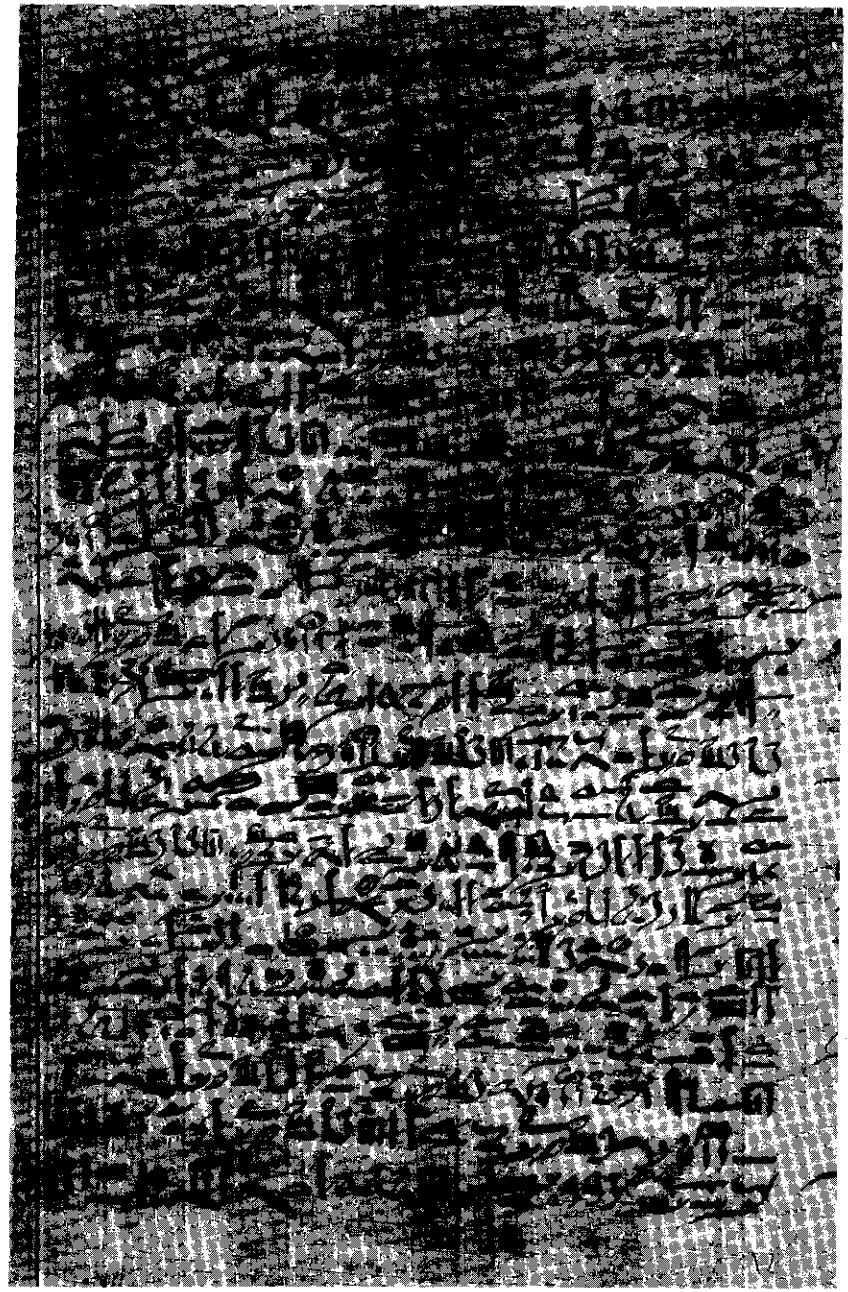

Fig. 1.2. A column from the Edwin Smith Surgical Papyrus (ca. 1600 B.C.), now in the New York Academy of Medicine.

Mesopotamian medicine displays many of the same characteristics as Egyptian healing practices. Babylonian clay tablets, like Egyptian papyri, contain case studies, systematically organized by type, many of them revealing careful observation of symptoms and intelligent prognosis. Mesopotamian healers displayed equal skill in surgery and the preparation of pharmaceutical remedies. As in Egypt, a certain amount of medical specialization developed—different categories of healers coming to have somewhat different specialties and functions. And again we find healing intimately mingled with religion and with practices that we would now view as magical. Disease was regarded as the result of invasion of the body by evil spirits (owing to fate, carelessness, sin, or sorcery). Therapy was directed toward elimination of the invading spirit through divination (including the interpretation of astrological omens), sacrifice, prayer, and magical ritual.[31]

This brief sketch of Egyptian and Mesopotamian contributions to mathematics, astronomy, and the healing arts offers us a glimpse of the beginnings of the Western scientific tradition, as well as a context within which to view the Greek achievement. There is no doubt that the Greeks were aware of the work of their Egyptian and Mesopotamian predecessors, and profited from it. In the chapters that follow, we will see how these products of Egyptian and Mesopotamian thought entered and helped shape Greek natural philosophy.

TWO
The Greeks and the Cosmos

THE WORLD OF HOMER AND HESIOD

We know nothing of Homer, reputed author of two great epic poems, the *Iliad* and the *Odyssey*. The poems, which recount heroic adventures associated with the closing days and aftermath of the Trojan War between the Greeks and Troy, are clearly the products of a long oral tradition, having roots that go far back in Greek history to the Mycenean age (before 1200); they appear also to have been influenced by non-Greek epic traditions from the Near East. They were perhaps committed to writing in the eighth century, but whether by one man (Homer) or several remains a matter of dispute. Whatever their precise origin, the *Iliad* and *Odyssey* became the foundation of Greek education and culture and remain among the best measures we have of the form and content of ancient Greek thought.[1]

Alongside Homer we must place Hesiod, who flourished around the end of the eighth century. To Hesiod, the son of a farmer, two major poetic works are attributed: *Works and Days* (which includes, among other things, a manual of farming) and the *Theogony*, which recounts the origin of the gods and the world.[2] Hesiod gave the gods a genealogy and, together with Homer, defined their character and the functions over which they presided. It was through the joint influence of Homer and Hesiod that the twelve gods of Mount Olympus were chosen from a plethora of local deities to become the gods of the Greeks.

Among the Olympians was Zeus, portrayed by Homer and Hesiod as the greatest and most powerful of the gods, lord of the sky, god of weather, wielder of lightning bolts, upholder of law and morality, and father of all. Hera, his sister and wife, presided over weddings and marriage. Poseidon, brother of Zeus, was god of both sea and earth, author of storms and earthquakes. Hades, another brother, was lord of the underworld and