ROUTLEDGE

A History of Science in World Cultures

VOICES OF KNOWLEDGE

SCOTT L. MONTGOMERY and ALOK KUMAR

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To understand modern science, it is essential to recognize that many of the most fundamental scientific principles are drawn from the knowledge of ancient civilizations. Taking a global yet comprehensive approach to this complex topic, *A History of Science in World Cultures* uses a broad range of case studies and examples to demonstrate that the scientific thought and method of the present day is deeply rooted in a pluricultural past.

Covering ancient Egypt, Mesopotamia, India, Greece, China, Islam, and the New World, this volume discusses the scope of scientific and technological achievements in each civilization and how the knowledge it developed came to impact the European Renaissance. Themes covered include the influence these scientific cultures had upon one another, the power of writing and its technologies, visions of mathematical order in the universe and how it can be represented, and what elements of the distant scientific past we continue to depend upon today. Topics often left unexamined in histories of science are treated in fascinating detail, such as the chemistry of mummification and the Great Library in Alexandria in Egypt, jewelry and urban planning of the Indus Valley, hydraulic engineering and the compass in China, the sustainable agriculture and dental surgery of the Mayans, and algebra and optics in Islam.

This book shows that scientific thought has never been confined to any one era, culture, or geographic region. Clearly presented and highly illustrated, *A History of Science in World Cultures* is the perfect text for all students and others interested in the development of science throughout history.

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To our families:

Kiran and Aarti
Marilyn, Kyle, Cameron, and Clio

Love and knowledge, endless roads whose dust is gold

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Preface

This book was written to serve readers in several ways. First, we present a summary of scholarly knowledge about scientific development in eight of the world's major civilizations. We have based this on our concept of a *scientific culture*, explained in the first chapter. Our choices of which fields and civilizations to cover, meanwhile, reflect those we feel have had more historical influence over time.

A second goal is to offer analyses and conclusions about pre-modern science that readers will hopefully find informative and thought-provoking. Contemporary scholarship, after all, does not view the history of science as a gallery of labeled discoveries and inventions but instead as a living branch of intellectual history. Such a history requires active reflection as well as knowledge and touches of originality in interpretation.

Third and last, each chapter provides little stories of an idea, innovation, or event that connect the scientific past – sometimes the very distant past – with the present. This is one of the ways in which we hope to convince the reader that the intelligence and achievement of former civilizations remain very much alive in contemporary scientific thought and practice.

This suggests we say a few words about the level of information. The great majority of the material we cover in an introductory way, with most of each chapter focused on cultural and political background, followed by discussion of specific fields of knowledge, particular thinkers, texts, institutions, technologies, and so forth. Another, smaller portion of the chapter will take up more technical details, for example a numbering system and how it was used or a type of metallurgy and its processes for making bronze or steel. None of this material requires anything more than high school science to comprehend, yet it may appear challenging to some readers. Much of it, however, is written in a way that teaches basic scientific ideas as well as treating the historical subject at hand.

This type of coverage reflects our strong belief that intelligent readers should have access to a diversity of materials that can engage them on different levels. There is another point we would make here: such diversity shows beyond any doubt that civilizations even thousands of years ago were fully capable of highly sophisticated technical thought.

* * *

Books are never the products of their authors alone. The debts we have acquired in writing this one need to be mentioned.

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1 Cultural diversity and the scientific endeavor

Science knows no single country, because knowledge belongs to humanity.

Louis Pasteur

Francis Bacon, who lived from 1561 to 1626, is considered one of the founders of the Scientific Revolution and a major figure in England's Renaissance. His famous work, *Novum Organum* (The New Instrument, 1620), says that "discoveries are new creations" and hold the highest place among human achievements. We must study them, Bacon said, because they have put new powers into human hands and altered the known world. We can see this

> nowhere more conspicuously than in those three [discoveries] which were unknown to the ancients . . . namely, *printing*, *gunpowder*, and the *compass*. For these three have changed the whole face and state of things throughout the world . . . such that no empire, no sect, no heavenly force seems to have exerted greater power and stimulus in human affairs.

Bacon was an extremely erudite man. Not only was he Queen Elizabeth's Chancellor, elevated to the title of Lord Verulam, he also authored dozens of works on many subjects, including history and science. Where, then, did he think the three great inventions he mentions were made? Bacon said their origins were "obscure and inglorious." He might well have guessed that they came from ancient Greece, for he also claimed: "The sciences we possess have almost all descended from the Greeks. For what Roman, Arabian, or later writers have added is not much or of much importance."

Lord Verulam was much mistaken. A scholar of his own country who had lived three centuries earlier could have informed Sir Francis of his error. Roger Bacon (c. 1220–1292), a Franciscan friar, devoted much of his adult life to the study of what was then called the "new knowledge" and which included the rich legacy not just of Greece, but of Islam, India, and China brought to Europe during the preceding hundred years by translations from Arabic into Latin. Friar Bacon had been asked by Pope Clement IV to write a summary of this knowledge and how it might impact Christian theology. The result, Bacon's *Opus Majus* (Greater Work), completed in 1267, is a major entry in the history of European science. If Lord Verulam had but consulted it, he would have found that, far from owing all to the Greeks, much of the science that Europe possessed came from the works of Alhazen (al-Haytham, 965–1040), Algazel (al-Ghazali, 1058–111), Avicenna (Ibn Sini, 980–1037) and Alkindus (al-Kindi, 801–873), to name but a few.

Should we forgive Sir Francis his ignorance? Bacon was a contemporary of Shakespeare, who provided many references to the greater world in his plays, particularly to Islam. "All the perfumes of Arabia will not sweeten this little hand," says Lady Macbeth in Act V Scene 1. Behind this statement lay the fact that a good many chemical techniques of distillation and extraction essential to perfume-making had come to Europe via Islamic science. Moreover, Shakespeare was not the only poet of pre-modern Britain who knew of such things. Geoffrey Chaucer (c. 1343–1400), in his *Canterbury Tales*, tells us of an excellent physician who is described in this way:

With us ther was a Doctour of Phisyk
In al this world ne was ther noon him lyk
To speke of phisik and surgerye, . . .
Wel knew he the olde Esculapius,
And Deiscorides, and eek Rufus,
Old Ypocras, Haly, and Galien,
Serapion, Razis, and Avicen

Chaucer's doctor is a learned man but not excessively so. He is familiar with the classic texts in medicine as understood by journeyman physicians of 15th century Europe. He knows the Greek god of medicine and healing, Asclepius, as well as the four great physicians of the classical world: Hippocrates, Rufus of Ephesus, Dioscorides, and Galen. He also knows the more recent classics of later writers, the 9th century physician Serapion the Elder, of Syria, as well as Rhazes and Avicenna, Persian thinkers and physicians of the 9th and 10th centuries, respectively.

Francis Bacon, it seems, knew less than he should have. Celebrating the Greeks while ignoring the Arabs was unbecoming of a man otherwise so knowledgeable. Today, nearly four centuries later, the history of science is a mature discipline, and so we might assume an oversight like Bacon's is no longer possible or acceptable. Among scientists and the educated public, too, a wider appreciation for the cultural diversity of pre-modern science surely exists. And yet – what if this were not the case?

In 2000, the American Association for the Advancement of Science (AAAS), the largest scientific organization in the world, published an interesting chart. It was a timeline of the 100 most important scientific findings in history – thus, a kind of updated version of Bacon's three great discoveries that changed the world – to accompany an article titled "The Endless Pathways of Discovery." Many different types of inventions, breakthroughs, and scientific ideas were included, as we would expect. But looking more closely, we find that the ghost of Lord Verulam might well have had a hand in its making. There are striking flaws to this chart that are beyond debate and that send us immediately back to the "obscure and inglorious" problem.

First, nothing before 600 B.C. is included. Anything that happened before this date is relegated to a "prescientific era." This leaves out all of ancient Egypt, Mesopotamia, India, and China, for example, over the course of more than 2,000 years, whether we consider metallurgy, mummification, or mathematics. Second, by far the greatest number of advances are younger than 1600; science, therefore, is inexorably modern and sprang to life full-grown, like Athena, goddess of wisdom, from the head of Zeus. Third, and most unfortunate, there are virtually no discoveries outside of ancient Greece and Europe. This means that no civilizations beyond these borders ever contributed knowledge or innovations that are worthy (India is given one mention for having invented the "zero," while the Hindu and Mayan "skywatchers" are also given one mention). Even Bacon's three world-changing discoveries find no place here.

What does this tell us? That there remains an enormous gap in understanding regarding the development of scientific thought through history. Though scholars have firmly established the long, multicultural nature of science's history, little of this has yet to penetrate beyond specialist awareness. Students in both the humanities *and* the sciences are only rarely exposed to it. Even history of science courses themselves tend to remain overwhelmingly focused on the modern period, i.e. Copernicus and after.

Why does this matter? Because it warps our understanding of the past and thus the present. It does this by ignoring an essential truth about science itself. Scientific work and thought have never belonged to one race, one gender, one social class. Nor have they been confined to one time period or one culture or one part of the globe. On the contrary, scientific traditions evolved in *all* of the world's major civilizations from a very early period – indeed, advanced civilizations were based on such traditions from the very beginning. It turns out that the growth of science in Europe leading to the Scientific Revolution of the 16th and 17th centuries depended profoundly on such earlier knowledge and would not have been possible without it. In a thousand ways, modern scientific practice is irretrievably rooted in this past. Cutting away these pre-modern roots leaves a damaged view, one that risks the provincial satisfactions of a colonial eye.

It is to help correct such a state of affairs that we have written this book. Science, we would say, has always been a world effort, pursued by different peoples from different linguistic, ethnic, and religious origins, in sometimes distantly separated, at other times overlapping, parts of the world. It has advanced at different levels, often with radically different goals and inventions that nonetheless seek to address similar fundamental needs, each civilization, therefore, developing its own scientific culture.

We in modern society today are the beneficiaries of this diverse effort. How so?

Much of it has a daily presence in our lives. Consider something as basic as the seven-day week. Where did it come from? It originated with the Sumerians, who assigned each of the visible planets (including the Moon and Sun) and, therefore, planetary gods, to its own day. Had there been another world between Mars and Jupiter instead of an asteroid belt, human beings in the 21st century would be organizing their existence around a week of eight days (six days of work, two days off?). After the Sumerians came the Babylonians, who developed a base-60 arithmetic system, by which they divided each hour into 60 minutes and each minute into seconds and a circle into 360 degrees. Another simple but profound example: the symbols now used everywhere for numbers (0, 1, 2, 3 . . . 9), often referred to as "Arabic numerals." In fact, these were invented in India, then adopted by Persian-speaking mathematicians who inhabited the western part of the country. Their texts, in turn, were translated into Arabic during the 8th and 9th centuries, after which the symbols became widely used in Islam and were introduced to Europe during the 12th century Renaissance, when the greater portion of science in Arabic was rendered into Latin. Not knowing their true origin, nor the complex journey they had taken, European translators attributed the numerals to their Arabic sources. This included the zero, an Indian innovation of tremendous power and importance.

Every time we employ these symbols today – whether to record an observation, calculate a physical change, or do a homework problem – we make contact with scientific cultures of the past, with mathematics of the Hindus, Persians, Arabs, and medieval Europeans. None of these cultures, in other words, lie coated in dust or frozen behind glass. They are part of the organic body of contemporary science, no less than Galileo or Darwin. The history of scientific knowledge defines a living history that the world utilizes every minute of every day.

Definitions

The character of science today

Before going further along these lines, we need to define our terms. What do we actually mean by "science"? A reasonable working definition might go like this: *science is the use of evidence to construct testable explanations (hypotheses, theories) and predictions of natural phenomena, as well as the knowledge generated through this process*. Such is how the National Academy of Sciences in the U.S. defines "science," and it was no small challenge to get agreement on it. The reason such a definition is challenging comes from the vast landscape of varied work and thought that comprise science – encompassing everything from field work on Arctic caribou to the study of subatomic particles with the Large Hadron Collider. Only a broad statement could hope to include such diverse labors.

A scientific theory, on the other hand, brings together a wide range of facts, observations, and other evidence and explains how they are related and why they occur. A theory in science is not a guess or a speculation, as in common speech ("I have a theory about why he does that. . . . "). It is an entire explanatory system, a very powerful one, assembled over time and subjected to constant re-examination and testing as new evidence comes to light. One of the fruitful aspects to such a theory is that it often reveals new forms of evidence and new interpretations of older information. It also has the ability to make certain types of predictions, always, however, with significant margins of error.

In all cases, reassessment and, when needed, revision of a theory are key: scientific theories *do not stand still*. This helps make clear why such static (non-evolving) ideas as creationism and intelligent design do not at all qualify as alternatives to the theory of evolution, which has continued to change since Darwin's lifetime. Other examples of major theories include: big bang theory, plate tectonic theory, quantum theory, and the theory of relativity, all of which represent the best elucidations of their phenomena that science can produce thus far.

Scientific work today, as practiced in research institutions, has some other elements that help determine its success and credibility. Scientists, that is, are willing to:

- Share their ideas, methods, and results with other scientists.
- Offer their work up to independent testing, thus to validation or invalidation.
- Abandon or modify accepted conclusions when confronted with new and more complete or reliable evidence.

Sharing of work and findings is mainly done in two ways: publication and collaboration. Scientific journals, which now probably number more than 20,000, reach a worldwide audience due to the Internet. Collaboration, meanwhile, has more and more become the norm, as reflected in the fact that the great majority of technical papers now have multiple authors. In March 2010, the journal *Physics Letters B* published a paper based on research at the Large Hadron Collider that had 3,222 authors from 32 nations. This may seem extreme, yet it is only a scaled-up version of what is happening elsewhere in science – researchers from different backgrounds, different areas of expertise, different cultures also collaborating on fundamental problems.

The three elements listed above provide a basis for science to correct and improve its knowledge over time. They also render scientists less forgiving where results cannot be duplicated or where cheating and fraud are concerned, and they can make it more likely that this kind of deceit is detected. The famous 1989 case of "cold fusion," put forward by Stanley Pons and Martin Fleischmann, is an example of a finding that could not be replicated but was not deemed to be fraud. A well-known example of the latter is South Korean researcher Hwang Woo-suk, who, in the early 2000s, published faked results claiming he had found an efficient way to create human embryonic stem cells by cloning. Fraud was uncovered when ethics violations involving female donor eggs came to light, leading to a detailed investigation of the relevant research methods and materials. Such examples show that scientific work is held by its practitioners, and by society in general, to very high standards of rectitude and transparency.

This should tell us, then, that applying our three elements of scientific practice to domains like politics, religion, and business would be unthinkable. The reason isn't that these other domains are by nature unscrupulous. It is rather that different types of knowledge and understanding – symbolic, metaphoric, spiritual, exclusive – are the rule. These cannot be rigorously tested, or, in the case of commercial enterprise, fully exposed in public. In many cases, there are not clear facts or forms of evidence that can be called upon for support. It is also true that there are not always strong and consistent guidelines for honesty in these domains. Nor is collaboration a common factor where competition and proselytization are the rule.

The character of pre-modern science

How, then, should we apply these ideas about modern science to the pre-modern era? Such is a question that has attracted a great deal of discussion, debate, and dismissal.

Scientific theories in the modern, secular sense did not exist for the great majority of time before the Scientific Revolution. Because of this, searching for hints and flashes of the "modern" across the millennia since civilization began would be of little value. The history of science would then be a small handful of polished fragments, like scattered pieces of rounded glass on a beach.

What we see in the pre-modern past instead are continuous traditions that largely combine the domains we call today "science" and "technology." In other words, we do not see science as an end in itself but rather as knowledge with human purposes and social goals; "applied science" is another appropriate term. Very often, an understanding of natural process – sediment flow in a river, for example, or fermentation – came from a goal-based effort, such as building a flood control system or making beer and wine. Solid understanding of nature and natural process was also used in, or derived from, activities like the production of food, weapons, tools, clothing, jewelry, the creation of buildings, reading of the weather and also certain religious ceremonies. What we want to know, then, as students of history, are the forms of such knowledge and the ways in which civilizations produced it.

We will find, in fact, that these forms were neither haphazard nor arbitrary. A great deal of the understanding that existed was gathered into systems that also included religious, social, and sometimes political and ethical elements. The fundamental idea that the universe and everything in it obeyed an underlying order was shared by every ancient civilization we will be examining. Some civilizations, like Mesopotamia, India, and Greece, viewed this order as mathematical and also moral/ethical; others, like Egypt and Mesoamerica, saw it as a direct reflection of the divine; still others, like China, understood it as a result of eternal and primordial transformations that were not wholly divine or secular. Ancient peoples, that is, created systems of principles about how nature worked. These systems were not rigorous or theoretical in the same sense as today, yet they acted to guide the development of new knowledge about how nature worked and also the place of human beings within the whole.

Those who performed what we would call scientific type work, whether this be astrologers studying celestial motions or a mathematician trying to turn a square into a circle of identical area, did share their ideas, methods, and results with others. Indeed, such sharing – including that with other peoples – defines one of the most important dimensions to pre-modern science. Ancient Egypt, Mesopotamia, and India had strong influences that flowed from one to the other, and their combined advances proved crucial to the Greeks. Islamic science drew heavily from

Greece but also from India and China, who had earlier profited from exchanges of their own. Vast portions of this combined learning then found its way to Europe, where it took centuries to absorb. Influence, based on sharing, is very much part of the pre-modern character of science.

In the beginning . . .

When did scientific thinking begin? This, of course, is a difficult and fascinating question. Simply asking it makes us think more deeply about history in this domain. Interpreted a bit leniently, our definition of science would allow us to go back a very long way, to hunter-gatherers in Africa or to their spread to the Middle East, Asia, and Australia. From an early time, *homo sapiens* had to use observation to build systematic knowledge about animal behavior and anatomy, as well as the life cycles of edible plants, and various cycles in nature, like the seasons. They learned to read the stars to find their way and, because they were hunters and, often enough, nomads, they came to understand details of the land, the ebb and flow of rivers, and weather signs. They had to experiment to find which stones and types of bone, ivory, and wood could be used to make the best tools and weapons, and they had to organize this knowledge in order to pass it down, teaching it to each succeeding generation. Similar skills of experiment were employed to create and control fire and to employ it in various ways for cooking, drying, warmth, lighting, and heat-treating stone and wood. Thus, it can be well argued that aspects of science were there from the beginning and were required for human survival itself.

For some readers, calling any of this "science" may seem overly generous at best. Some authors on the subject have used terms like "pre-science" to separate the vast majority of human history from real scientific thought, which is correlated with the modern era only. Yet, as many historians of science now say, no such clear boundary exists or even makes sense.

Let us then consider a scene sometime later, about 12,800 years ago, in northern Europe. This was the beginning of the Younger Dryas event, an abrupt climatic shift when glacial conditions – deep cold and drought – returned to northern Europe in a mere decade or two after nearly two millennia of progressive warming. The first few generations of people living through crisis. They faced enormous stress and many challenges from the rapid disruption of the environment that took place. The clothes they wore were no longer adequate; the animals and plants they needed grew weak and died off or migrated away. Streams and lakes froze for much of the year; snow remained on the ground until summer. Patterns of rainfall, wind, and sun all changed dramatically. In the end, communities of hunter-gatherers likely fragmented, with small groups forced to migrate themselves, probably southwards, perhaps following the remnants of game on which their diet, rituals, and beliefs depended.

But they survived. Their numbers fell, then began to recover. Some groups had members with superior knowledge of plants, animals, and stoneworking. These members now had to search out new edibles and new sources of rock for tools. They had to experiment with unfamiliar species and stones, test their utility, rank their excellence, map their locations, teach others, learn from other groups when possible. As the dry cold of the Younger Dryas reached its peak after about 20 or 30 generations, the people would have lived through several or more new habitats. They would have been forced to repeat the cycle of exploration, testing, and adaptation in areas where food was less plentiful. It is clearly no accident that they began to selectively harvest wild grains, which they processed by grinding, and learned how to cultivate at an introductory level. They did not survive by chance, in other words, nor by mere trial and error. A degree of system in their knowledge gave them essential capabilities.

Such a scene leaves us with an unexpected idea. Perhaps the truth is that humanity has never lived without some measure of tested understanding about the natural world that we would recognize as having aspects of science. Perhaps science has been there all along, from the beginning, *homo sapiens* and *homo scientia* defining a single species.

* * *

Meanwhile, there is little argument among anthropologists and archeologists that a significant amount of genuine scientific knowledge played a role in what many have called the greatest transformation in human society. Indeed, the transition to agriculture, known as the Neolithic Revolution, could not have taken place without specific scientific and technological advances. A few of these advances include:

- determining which plants could be best domesticated, ways to improve these through cross-breeding;
- determining the best times for planting and harvesting, therefore knowledge of the seasons;
- building systems of irrigation, discovering uses of fertilizer, identifying pests;
- breeding of animals, developing detailed knowledge about their reproduction, health, nutritional needs;
- use of the stars for chronology, construction of calendars, measurement of time;
- developing and improving medical knowledge, use of herb-based medicines, surgery, salves, dentistry;
- developing systems for measurement, counting, calculating, dividing land;
- identifying clays for pottery, improving these through mixing, adjusting firing temperatures; and
- building the first major human structures with native stone, mud, wood, earliest forms of mortar.

Major discoveries and innovations, therefore, were required every step of the way for humanity to make the fundamental move to agriculture roughly 11,000–12,000 years ago and, therefore, into settled villages, towns, and, eventually, cities. Clearly, observation and experimentation – including informed trial-and-error based on actual knowledge and performed on a fairly systematic basis – were key elements. A specific example can help to show this.

In the lower Jordan Valley, a few miles north of Jericho, lies an early Neolithic town called Gilgal I where fragments of a particular edible fig have been found. This fig came from a tree that is infertile, thus cannot reproduce, yet generates edible fruit. It represents a random mutation of normal fig trees and occurs rarely and sporadically in nature. The reason this particular tree attracted notice from humans is that its figs do not bear the embryos of wasps, which normally pollinate fig trees.

At some point between 11,400 and 11,200 years ago (determined by carbon dating), people in Gilgal discovered four things about this special type of fig tree: 1) it exists; 2) all of its fruit is edible; 3) it doesn't produce new trees; and 4) it can be artificially reproduced by cutting new shoots, planting them in the ground, and watering them sufficiently. Hundreds of fragments of the resulting figs have been found in the houses at Gilgal, strongly suggesting that they were a common part of the local diet and that cultivation was done on a organized, methodical basis. Some of the fragments, moreover, were found together with wild barley, oats, and acorns. We can surmise that the early form of horticulture practiced at Gilgal represents a phase of the agricultural revolution just before grains and cereals, as well as livestock, were fully domesticated. But the key fact here is that in these desiccated little fragments of fig we have an incontrovertible example of how humanity used observation and experiment to expand its food sources. This was science employed and applied.

The beginnings of agriculture happened in several river valley civilizations of the world between about 13,500 and 7,000 years ago. In each setting, people cultivated different crops: along the Yellow and Yangtze rivers of northern China, millet and rice were domesticated; in the Indus Valley, wheat and barley; across the Fertile Crescent, a variety of founder crops, including wheat, barley, peas, flax, and lentils; similar crops, as well as cotton, were raised along the Nile Valley; and in the highlands of Mexico, maize became the dominant food. Different systems of irrigation, water containment, and flood control were also invented by each civilization. The same is true for the astronomy used to construct calendars.

In each setting, therefore, a separate culture of scientific and technological advancement made agriculture possible and, indeed, successful. But this was not all. Well before the beginning of the Christian era, contact among four of these cultures – Egypt, Mesopotamia, India, and China – had created the conditions for the sharing of knowledge and foods. Wheat and barley were introduced to all these civilizations, while rice moved from China to India, Persia, Southeast Asia, and beyond.

From the beginning of the Neolithic Revolution, then, scientific knowledge proved itself vital. Certainly it did not exist as separate categories of field investigation, laboratory analysis, and cultivar testing as it does today. Yet parts of all these activities were undoubtedly present at certain times, such as when new crops were imported and adapted to different climate and soil conditions. Over the millennia and centuries, each civilization developed its own hybrid system of technical knowledge that nurtured traditions of study, learning, exploration, and sometimes stasis too. But in the end, the diversity of pre-modern science meant a richer legacy for the modern era.

* * *

It would be fair, at this point, for the reader to ask for a few examples of major advances in some of the major civilizations that grew out of the Neolithic Revolution and that rose even later. Since the following chapters will provide a great deal along these lines, here we offer but a brief list:

Ancient Egypt – industrial chemistry, prosthetics, and pregnancy tests
India – the sine function, place notation, and rust-free steel
China – papermaking, printing, and gunpowder
Islam – algebra, spherical trigonometry, theory of vision, and alchemy
Mesoamerica – prediction of solar eclipses, vulcanized rubber, and contraceptives

Short as it is, a list like this tells a great story, repeated time and again. Every major world civilization developed materially on the back of knowledge about the natural world. Their people built great cities using animal and human labor, as well as many types of materials, some man-made, which meant some understanding of geology, physics (forces), and chemistry. Their systems of irrigation imply a grasp of hydrology, and their mathematics were invented to handle the partitioning of land, the selling and buying of goods, and the distribution of food. Geologic knowledge was also needed to locate and identify ores for mining, as well as gems for jewelry and religious uses. The growth of metallurgy demanded a detailed awareness of how each type of ore responded to certain levels of heating. Experiments in chemical effects were performed to determine optimal compositions for pottery vessels and to make such things as cosmetics, perfumes, paints, ink, and dyes. To protect their cities and farms, and to conquer others, each civilization invented a variety of weapons and defenses and strategies for organized conflict and dealt with the dead and wounded. War, of course, has always acted to stimulate scientific activity. Finally, most of the civilizations mentioned above developed their own sophisticated forms of medicine – not just incantations or spells but techniques of surgery, types of drug therapy, use of prosthetics, anesthesia, healing salves, and much more. Overall, science and technology permeated ancient culture, without any doubt. In a certain sense, we degrade these early civilizations by denying them the knowledge of the natural world that they so obviously had.

This book

This book, then, is not about controversial things, but instead about established truths of history. Drawing on the work of many excellent scholars, our goal as authors is to make this information more widely available for teaching and learning. It is our main theme here that modern science has deep roots in a pluricultural past that has not been widely acknowledged but needs to be. Late Medieval and Renaissance Europe inherited and transformed the science of much older civilizations, and this knowledge helped make possible the Scientific Revolution.

Can we say that thinkers like Isaac Newton, Rene Descartes, and Robert Boyle were directly influenced by the combined learning of the past? The evidence is indisputable. When observed from the towers of Oxford, Cambridge, and Paris, where study of "oriental" topics, including the sciences, were established by the 17th century, the connections are both obvious and inevitable – if not sufficiently well-known.

Revealed, then, are key truths about science itself. We have noted one of these: that while living in the present, we trace the contour of pre-modern science in a hundred ways, from the numerals we use to the medicines we take. Another truth is that the work and thought of the sciences have never belonged to one people, race, gender, or class. Nor have they been confined to one time period or culture, ancient or modern. In its historical embrace, science brings together a range of civilizations and cultures.

This book intends to narrate something of the *global* history we are discussing. Covering Egypt, Mesopotamia, India, China, Greece, early Islam, and Mesoamerica, we show a wide range of scientific and technological achievement and how the major part of it came to nourish Europe later on. The chapters that follow emerge out of the teaching, research, and broader interests that both of us have pursued over the past two decades. Both of us are professional scientists (Kumar a physicist, Montgomery a geoscientist), who have expanded our intellectual work into the history of science, cultural studies, translation, and international relations. Our coverage in these pages should serve as a solid introduction to the diversity of world science and its importance in world history.

This diversity can best be understood through the idea of a "scientific culture." This we define as the *collective knowledge and explorations of nature and its materials developed by a particular people in response to the specific demands and opportunities of their society*. In each case, we examine a scientific culture on its own terms, as an evolving dimension to each respective civilization. To do so, we avoid the historically misleading dichotomy between "western" and "non-western."[1] Neither do we engage in the sport of identifying who was first to discover or invent a particular advance – history is something more than an Olympiad for hanging medals. That Chinese technicians developed the use of coke for iron smelting five centuries before Abraham Darby in England tells us nothing by itself. More important are the reasons why this use evolved, what needs or questions it answered, how successful it became, and whether it was transferred to other peoples.

Reasons

There are other reasons for a book like this, which go beyond putting new knowledge on display. Indeed, these reasons return to the large value of history itself. First, the past deserves to be studied in order that we understand science more thoroughly as an evolving human enterprise. There is a natural tendency to think of scientific work solely in contemporary terms – laboratories, white coats, journal articles, data, grants, university posts, R&D companies, and so on. But all of this, historically speaking, is exceedingly new. Much of it is less than a century old and in the midst of change. Take, for example, the primary form of scientific publication up to the 20th century. The book has changed radically over time, from the writings composed by the great Brahmagupta (7th c. C.E.) in India, on palm leaves, to the works by al-Biruni (10th c. C.E.) of Persia, which were on paper, and finally *De revolutionibus orbium coelestium* (1543) by Copernicus, which appeared in print. We might be tempted to say, in the age of the scientific journal, that all of this is without consequence, the dust and debris of bygone eras. Yet consider: digital technology and the Internet have altered science profoundly, in flesh and bone, and this will continue. In the first several decades of the 21st century we are witnessing the next major stage of the "book," with the scientific journal now in the midst of a transition from print to electronic form. We are still struggling to comprehend what this means – what will scientific publication look like a few decades from now? Will we see the death of the research journal and its replacement by some other form, the single article perhaps or a non-print, open-access archive?

The point is that the transition science has now embarked upon has parallels in the past – above all, the change from handwriting to print. This actually happened twice, once in China during the Tang Dynasty (7th–10th c. C.E.) and again later in 15th–16th century Europe. Understanding these earlier episodes might well offer clues for what we can expect in the future. Modern science is as much a continuation of the pre-modern era as it is a break from it. The "Scientific Revolution," a title that implies the sudden overturning and erasure of all that went before, is mythic. Another value of history is that it shows that nothing is ever so simple. Other transitions for science still lie ahead.

Many scientists are surprised to learn that one of the greatest works of mathematical astronomy, written in 6th century India, took the form of a poem. This is the *Aryabhatiya*, consisting of 123 stanzas in Sanskrit. Are there other specimens like this? Most definitely. One would be *De Rerum Natura* (On the Nature of Things) by the 1st century B.C. Roman philosopher Lucretius, who wrote in hexameter Latin. Another is a short set of verses in the form of a Buddhist sutra by the early 19th century scholar Udagawa Yoan, introducing western biological nomenclature to Japan. This might lead us to ask: what do such writings imply about the relation between science and literature? Can we perhaps say that scientific texts even today try to tell stories of invention, experimentation, and discovery, or at least provide eye-witness accounts of the same?

Something else that we learn from pre-modern science: the most profound advances have commonly occurred during times of greatly enlarged cultural interaction. This would include the Han (3rd c. B.C.–3rd c. C.E.) and Song (10th–13th c. C.E.) Dynasties in China, classical and early Hellenistic Greece (5th c.–1st c. B.C.), the Gupta Empire in India (320–600s C.E.), the "golden age" of Islamic science (9th–13th c. C.E.), and Renaissance Europe. To these examples we might well add the present era. The 21st century collaboration among researchers from different nations is rapidly becoming a new norm, reflecting the globalization of science generally. For this we can thank the Internet once again but also the use of English as a global language. And here, too, we find precedents from the past: written Chinese in ancient and medieval East Asia, Greek in the eastern Mediterranean, Sanskrit in early India, Latin in medieval and Renaissance Europe, and, most extensive of all, Arabic across the whole of the Islamic world during its great period of scientific expansion.

The pluricultural past of science can offer one final insight, therefore. As it spreads throughout the world today, such that modern research overflows the handful of richer nations where it began into many developing nations, science has come home in a sense. For the great majority of its evolution, it was always a global phenomenon, always comprised of multiple cultures of the mind and the word. It is the task of these pages to reveal the truth of such words.

Note

1 A simple example: the sine function, invented in 6th century India, was later transferred to Islamic science in the 8th century, and then, in the 12th century, to Europe. The word "sine" originated from a mistranslation in Latin of the Arabic word *jiba*, which is itself a transliteration of the Sanskrit word *jya-ardha*, which means "half of a chord" (in a circle). To what degree does it make sense to call this "western" or "non-western"?

Further reading

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Floyd E. Bloom, 2000. "The Endless Pathways of Discovery," *Science* 287:5451, 229.

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2 Science in Egypt

Creating a civilization

> I had gone to the Mining region of the sovereign
> I had gone down to the sea
> In a boat 120 cubits long
> 40 cubits broad
> In which there were 120 sailors from the choicest of Egypt . . .
> Before it came they could foretell a gale,
> A storm before it existed
>
> Tale of the Shipwrecked Sailor (ca. 2,500 B.C.?)

These few lines are from a famous literary tale, probably composed during Egypt's Old Kingdom (2686 B.C.–2181 B.C.). It is a story about a fantastic journey where the sole survivor of a shipwreck learns that he can restore order to a chaotic world through the power of language and obedience to the laws of nature.

We can see this is a society that has explored its geology, discovered its riches, and put them to use. Technology is advanced; it can build ships of great size. A cubit was the length of an average forearm, about 53 cm (21 inches), making a ship of 120 cubits no less than 63 meters (208 ft) long. Boats of such scale imply a long tradition of seafaring, thus knowledge of navigation, currents, coastal geography. We see that numbers and measurement, thus basic mathematics, were well known. Finally, sailors could understand weather signs and interpret evidence from the sky and the winds. All these scientific elements, then, in an allegorical poem about life, death, and rebirth.

This isn't surprising. The history of science in Egypt spans no less than 3,000 years – from the unification of Upper and Lower Egypt under the first king, Narmer (3100 B.C.), when an era of magnificent achievement began, to the tragic burning of the Great Library at Alexandria (48 B.C.). A similar length of time would stretch from the founding of the Roman Empire to the year 2900 C.E., a date so far in the future we can't even imagine what modern science will look like. It is easy to see why other, later peoples, like the Greeks, felt such awe before its towering achievement.

Before we look deeper into this achievement, a caveat is in order. Ideas and beliefs that we would call religious permeated Egyptian thought. In such a context, no division between "science" and "religion" existed. We will pretend, however, that technical subjects can be discussed pretty much on their own for the sake of modern understanding. There is some justice to this; a significant part of Egyptian science was absorbed by other cultures, notably Greece.

Background

Surrounded and protected by deserts (Figure 2.1), the people of the Nile built a civilization from which an extraordinary number of monuments, statues, objects, and writings have been preserved – the Egyptians were great makers of things. All of this, including the pyramids, was based on technical knowledge. The greatness that was Egypt came directly from its science and technology.

Everything began with the Nile River. Roughly 5,500 years ago, the first complex societies formed in several of the world's major river valleys – the Tigris and Euphrates, Indus, Yellow, and the Nile. Villages combined into towns through conquest, then into larger political units until many diverse communities lay under a single ruling hand, a monarch or clan chieftain who sat atop a supporting priesthood and bureaucracy. But why river valleys? A major waterway, particularly in a dry climate, causes the land to burst into a winding spectacle of green wealth and flowering fertility. Plentiful freshwater and rich floodplain soils created a fabulous concentration of life and ecological diversity (Figure 2.2). For humans, this meant a wealth of food, materials (in river cliffs) for weapons and tools, herbs for medicines, skins and plants for clothing and medicine. A watercourse like the Nile also acted as a barrier to invading armies, while to the inhabitants it was a magnificent highway, stimulant to trade, the transport of resources, a source of cultural unity.

The Nile's ecology changed a great deal during the final millennium before written history. Prior to 4000 B.C., the Sahara was cooler, wetter, covered by grassland savannah and roamed by lions, wolves, jackals, giraffes, gazelle, monkeys, and wild cattle. By 3000 B.C., the region was drying into final desert, driving many animals south but leaving a complex system of belief among Egyptians, who viewed animal forms as earthly manifestations of gods. Over the next twenty centuries, humans had their own impact: trees of the floodplain were cut down; many waterfowl were reduced in number; a few animals, perhaps lions, were hunted to local extinction. Daily use of the Nile for so long, by a population that probably reached several million at least, was bound to take its toll. And yet, given the great length of time, far less damage was done than has been the case for rivers in just the past 75 years. Relations between civilization and the Nile were largely sustainable for millennia, an almost unimaginable thing today.

The Nile runs its last 1,300 km (800 miles) through Egypt. Here it has no tributaries and gets little rain. Small wonder the people who came to live along its perennial waters saw them as a divine creation, a ribbon of life through deadening sand. The Egyptians could place their faith in an orderly nature, ruled by cycles, and their belief that life continues in a different form after death should be understood against this background. The river ends in a great delta, a term from the Greeks, who applied their triangular letter to the Nile above all.

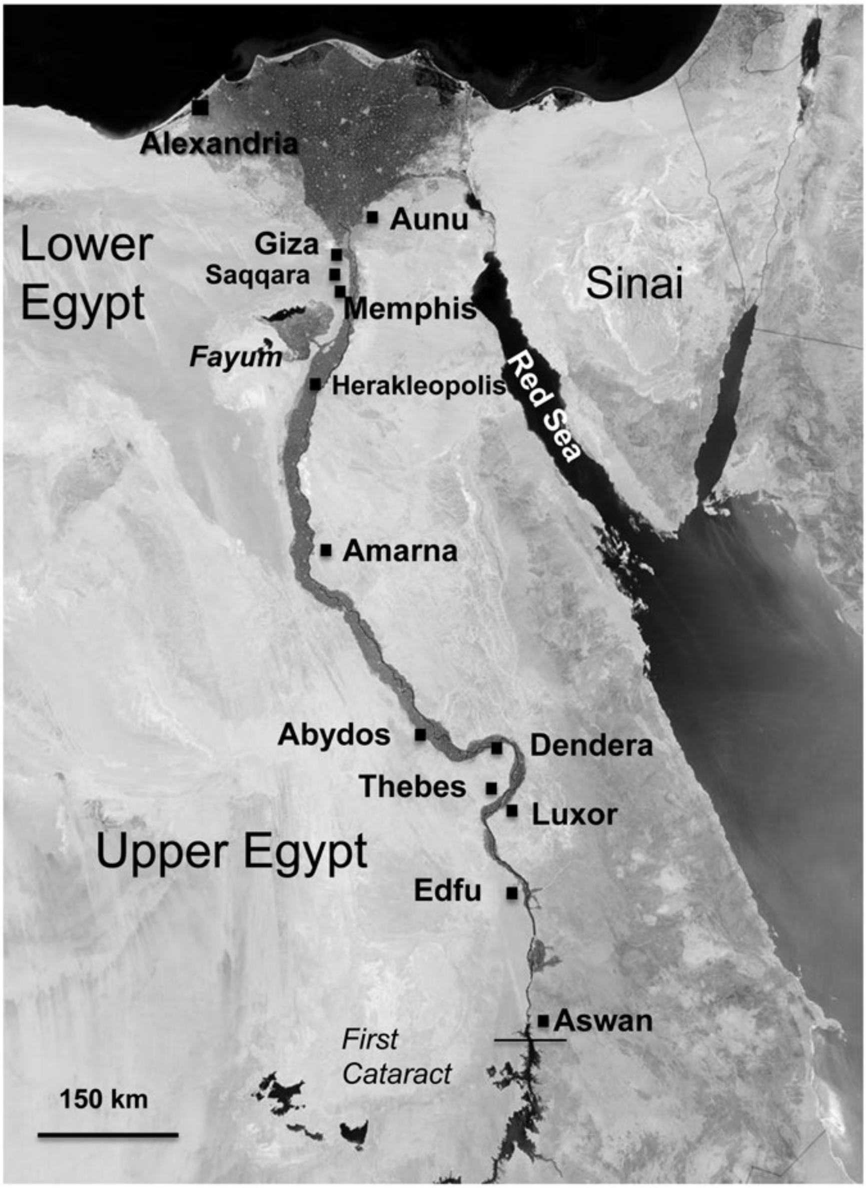

Figure 2.1 Map showing the major cities of ancient Egypt.

Before modern dams, large parts of the delta and the entire width of the Nile valley were inundated from June to mid-September, receiving a new layer of sediment. Flooding also washed away mineral salts in the soil, preventing salinization, which would have been toxic to crops. The floods were fed by monsoon rains in

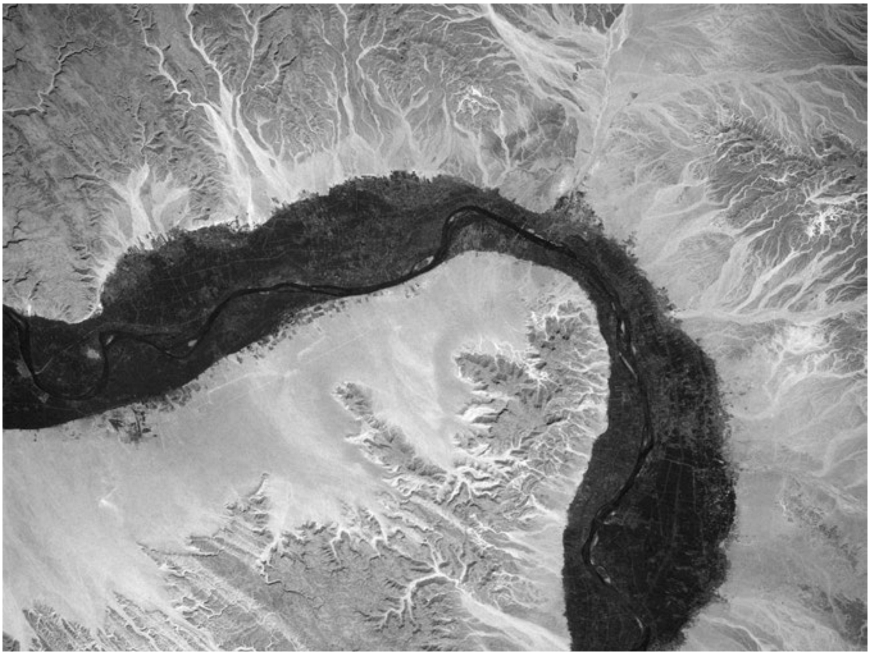

Figure 2.2 A satellite image of part of the "great bend" in the upper Nile, showing the width of the floodplain and the intense agricultural development within it. Courtesy of NASA Visible Earth.

the Ethiopian Highlands, where the largest tributary, the Blue Nile, carrying some 70% of the river's total water, begins in Lake Tana. This is a volcanic region, with nutrient-rich (calcium-, phosphorous-, potassium-bearing) silts and muds that wash into the river. Not far downstream are wetlands and swamps whose organic debris was also carried into the rising waters of the Blue Nile. All of this material came to be spread over the floodplain north of where it meets the White Nile tributary in Sudan. So regular was the flooding event that the Egyptians based their calendar and their reckoning of seasons on it. Growing food in the Nile Valley was far easier than anywhere else in the region, an enormous boon to Egypt's prosperity.

Such are clues about the Nile's importance to science. What about a specific example? The plant *Cyperus papyrus*, a wetland reed up to five meters (16 ft) tall, grew abundantly along the river's shallow banks. It has a long, green, durable stem and is capped by a spray of grass-like fronds. Observing its ability to bend in strong winds, the Egyptians found it could make things subject to repeated stress: rope, sandals, baskets, floor mats, mattresses, even boats. It also yielded food and medicine. But this still didn't exhaust its capabilities. When sliced open, peeled into layers, dried and pressed into sheets, it provided something of incalculable value: the first paper, papyrus (Figure 2.3). Rolled up into scrolls, it formed the

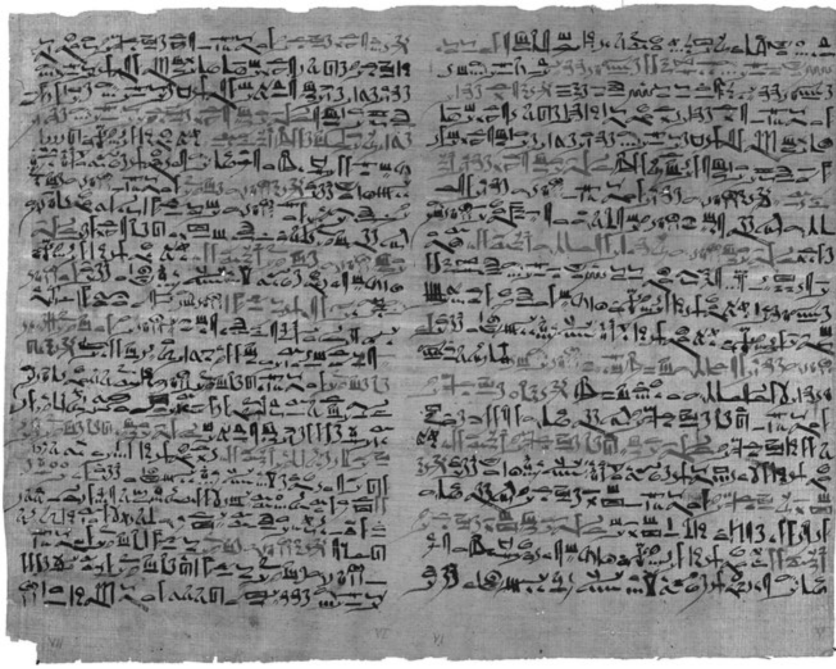

Figure 2.3 A picture of Plate 6 and 7 of the Edwin Smith Papyrus.

earliest books, first produced in the 4th millennium B.C. Amazingly, the technology to make papyrus was kept secret for more than 2,700 years. It finally had competition from parchment (dried and stretched skin from a calf, sheep, or goat), an innovation that began in Pergamum (Turkey).

Until then, Egypt held a monopoly, perhaps the longest in history. Paper was something nearly every culture in the Near East wanted (think of a company having control over word processing software for a thousand years). Egyptian merchants built a highly profitable export market. One of their largest buyers was the town Jebeil in modern-day Lebanon, which the Greeks called "Byblos" and used as the word for books (*biblia*). It is from this name, in fact, that the word "Bible" comes. Thus a technology of the pharaohs, using a plant from the Nile, proved essential to the Jews who set down a book that would change the world.

Food: Egyptian agriculture

Egypt was the most pleasant, cultivated society to live in during pre-Roman times. Its long periods of security and brief chapters of instability mark a contrast to other early river civilizations, like Mesopotamia or China, where wars were very frequent. What accounts for such a difference? Scholars often give a one-word answer: food.

Good soil, abundant water, endless sun: these made the Nile Valley an ideal place for agriculture with minimal labor. Nature was clearly on Egypt's side. But nature was not enough. The "gift of the Nile," as the Greek historian Herodotus famously called Egypt, needed knowledge of this nature and how to use it – the power of ingenuity and application. Without these, the country would have remained a scattering of hunt-and-gather settlements.

From papyrus scrolls, tomb paintings, and other sources, we know the Egyptians understood much about the Nile's plant life. At a very early stage, this helped them to develop an advanced agricultural system regulated by the annual flood event. When we say "advanced," what do we mean? If the Egyptians knew how to plant and reap according to levels of the Nile, they also built a system of irrigation to aid this process. They developed their own mathematics to solve practical problems related to harvests, food distribution, and field boundaries. Egypt also adopted crops and technology from surrounding peoples, especially those of the Fertile Crescent. A great deal could be grown in the Nile Valley that was not native to it. And the Egyptians, knowing this, became over time skilled at expanding their system to include new plants for other purposes, such as ornament, aroma, and medicine. The extent to which they nurtured biodiversity is revealed by the fact that roughly 2,000 different flowering and aromatic species have been identified from tombs, mainly of the Old and Middle Kingdoms. Egypt was the first civilization to practice ornamental horticulture and landscape design.

As always, everything began with the Nile. Unlike most other major rivers, the Nile flooded gradually. It began to rise in southern Egypt in early July, reaching flood stage by mid-August. Measuring stations, called nilometers, using notched rocks, were built along the river's course, allowing close comparison between flood levels of different years and good prediction of peak inundation (records of these levels were kept in temple archives). By late September, the entire valley was under water, usually to a depth of 0.3–1.5 meters (1–5 ft). Peak flood lasted two to three weeks. By mid-October, waters began to recede, and by December the river was within its banks again. Soils would dry quickly in the merciless sun, so to retain water for part of the growing season, which extended to mid-April or May, and to expand the total area for cultivation, the Egyptians devised an extensive irrigation system.

Using earthen levees, they made dike-enclosed reservoirs or basins, varying from about 400 to more than 1,000 hectares (1,000–2,470 acres), linked by sluice gates and canals. During flooding, basins were left open and so filled with water. When waters receded, the gates were closed, and the captured water would then keep the soil saturated. Gates and canals connecting different basins helped to distribute the water evenly. Fields thus remained wet for up to a month during the early, fragile period of crop growth.

The technology also existed to dig wells up to 100 m (330 ft), even through solid rock. These wells were used in some areas to supply water for crops and gardens during the dry season but more often to provide it to homes and gardens of the wealthy, to the royal palace, and also to tombs, via copper pipes. Natural pest control came from insect-eating birds, protected by royal decree. Levees did have to be repaired each year and canals dredged, but the overall amount of work for a good harvest was quite small.

The system was simple in concept and effective in practice. It was based on the hydrology of the river and used the most fundamental, non-invasive method of transferring water between locations: gravity. The system was ancient, even by Egyptian standards. Evidence of it appears on one of the oldest known scenes in Egyptian art, the so-called mace head of the Scorpion King, carved in low relief on limestone and dated to about 3100 B.C. (Figure 2.4). It shows the king of Upper Egypt, likely the first pharaoh, holding a hoe for planting and under him a series of workers laboring on levees around basins with captured water. Egypt's irrigation system, it seems, thus began in the Predynastic Period (>3100 B.C.).

Is it strange that pharaoh, a god in his own right, would be shown holding a common farm tool? But agriculture was the basis of Egyptian civilization. A gift from the gods, it embodied divine order, natural cycles, and the place of humans in the greater scheme of existence. Pharaoh stood at the top of the human ladder, as one who brought the gods' blessings and protected the many who depended on this. The hoe in pharaoh's hand is a sign of his role.

Figure 2.4 Detail of the "Scorpion King" mace head, showing the king holding a hoe and, below him, men apparently working on dikes or a canal. The mace head is about 25 cm (10 inches) tall. © Heritage Image Partnership Ltd/Alamy.

Most Egyptians were farmers. The government levied a tax totaling about 10–15% of the harvest, but it left agriculture in local hands, something that was both distinctive and beneficial. It meant political problems did not affect the ability of the country to produce food. That farmers had control over their fields may also help explain an even more unique aspect: Egypt did not have slaves for most of its history. The first mention of slavery, related to those captured in wartime, doesn't occur until about 1500 B.C., at least 2,000 years after the system of agriculture was established.

What did Egyptians grow and eat? Barley and emmer were the main grains. Both went primarily to make bread, with loaves of many different sizes and flavors. Lightly baked versions were used for making beer, the most widely drunk beverage.[1] Grapes were grown for eating and to make wine, but the latter was expensive. Beer production, like agriculture itself, was on a massive technological scale, with many refinements as to quality, taste, aroma, and texture. Yet these foods represent only a small part of Egypt's total menu, which also included many vegetables, fruits, spices, meats, and fish. Indeed, the diversity of foods that the Egyptians had available as early as the Old and Middle Kingdoms (~3000 to 1800 B.C.) is nothing short of stunning. Vegetables, for example, included beans, cabbage, celery, chickpeas, peas, onions, and lentils, among others. For fruits, there were apples, dates, figs, jujubes, olives, plums, pomegranates, and melons. And for spices, there was the choice of garlic, aniseed, cinnamon, coriander, cumin, dill, fennel, marjoram, rosemary, and thyme, among others (pepper was unknown). Sweetening made use of dates, figs, and honey. Cattle were raised in large herds, as were sheep, with goats and pigs also abundant. Though waterfowl, especially ducks, geese, pigeons, and quail, were widely consumed, Egyptians do not seem to have raised hens for eggs until the Ptolemaic Period (305–30 B.C.). Fish were caught in plenty by a wide range of techniques – nets, hooks, harpoons, spears, traps – according to images in scrolls and on buildings. In addition, there were plant-derived oils of varied properties and purposes, some for their scents, many for medicines, others for cosmetics, many more for religious uses, including embalming.

Most of this spectacular variety could only be enjoyed by wealthier members of society, who lacked for nothing. Bread, fruit, and beer were the main staples for ordinary people, though records show that men who worked in the quarries were also sometimes given vegetables and roast meat. In most years, Egypt's people had more than enough to eat. The upper classes regularly held banquets at which many different foods were served. Dining was a source of refinement, an opportunity to show off one's wealth, status, and sophistication. Music and dancing were routine, and guests were encouraged to eat and drink to excess. But such events were also expressions of Egyptian technology: musical instruments revealed craftsmanship and expert metallurgy and metalworking; chairs and tables could be folded and put away; jewelry worn by women and men included not only precious and semiprecious stones but also glass beads that had been made with a variety of vivid colors; manmade perfumes and scented oils filled the rooms with lovely smells.

That food was commonly plentiful does not mean a total lack of hard times. In years when the monsoons were weak, the Nile might fail to flood sufficiently or at all, and the majority of Egypt's food could not be grown. Storage of grain was done on a large scale, yet years of famine did occur – the famous biblical story of Joseph and Pharaoh's dream (Genesis 41) was an example known to antiquity. The so-called "dark age" that began after the sudden collapse of royal authority in the Old Kingdom, giving rise to the First Intermediate Period (2181–2040 B.C.), is documented by inscriptions that repeatedly refer to famine. Sediments from the Nile Delta show a thin zone of highly oxidized, red-brown silt, indicative of long-term exposure, dated at 2250–2050 B.C. Some Egyptologists now feel that each of the three intermediary periods, when social and political instability reigned, probably corresponds to a time of reduced flooding and fertility. Yet order returned – these periods were but dark punctuations between eras when food was seldom a source of worry.

Egypt thus presents the modern era with an important question. To what degree was this civilization, so dependent on, and integrated with, a single river and its plenty, the creator of a sustainable form of agriculture? Does it hold any lessons, positive or negative, for the present?

Mathematics

If its knowledge of plants and animals was tied to the Nile, this was just as true of Egypt's mathematics.

No society can live without time – ways to define and measure it. How did ancient people construct a calendar? They began with a recurring natural event that repeats itself once a year and could be accurately predicted. For the Egyptians, this was the rising in early July of Sirius, heralding the Nile's flood. Sirius is the brightest star in the northern sky, and its rising repeated every 365.25 days, nearly identical to the solar year. The year was then logically divided into three Nile seasons: *akhet*, or "the flood" (equal to our summer and fall); *peret*, meaning "growth" (winter/early spring); and *shemu*, "harvest" (late spring/summer). The Egyptians identified 12 months totaling 360 days, with 5 days added at the end of the year. These last days were dedicated to the five children of Nut (god of the sky and the heavens) – Osiris, Horus the Elder, Set, Isis, and Nephthys – who, together, helped ensure that the new year would come. The months were divided into three weeks of ten days, and the day into 24 hours, 12 each for daylight and night time. The number 12 was chosen based on bright stars, known as "decans," that rose during each night. Time during the day was measured by several instruments, including the shadow clock, built in the shape of a "T," with a slightly elevated cross bar whose shadow would progress down a marked, elongated stem. The most sophisticated was surely the water clock, based on the regular drip of water from one container to another. Earliest evidence of this technology in Egypt dates from around 1600 B.C. but seems likely to have been in use well before this time.

How, then, did the Egyptians calculate? Most of our knowledge comes from just two documents, the *Moscow Papyrus* and the more well-preserved and important *Rhind Papyrus*, both dating from the 2nd millennium B.C. These contain sets of problems, including practical ones, followed by solutions, suggesting they were written as instructional manuals. Another clue in the *Rhind Papyrus* is that the problems are given in red ink, while the solutions are in black. The papyrus consists of 14 sheets glued together, with each sheet 32 cm (12.6 inches) tall and the whole document 5.1 m (16.8 ft) long. In its first part, it has reference tables as well as arithmetic and algebraic problems and formulae. It seems, in other words, that the textbook as a means of passing on knowledge is a very old idea.

The Egyptians had a base-10 numeral system, as we do today, without place-value notations, though they also experimented with base 12. Preference for base 10 may have come from the number of digits on the human hand, but this is speculative. Figure 2.5, meanwhile, shows that the Egyptians created different symbols for numbers up to ten and then for multiples of ten. When we try to work with this system, we quickly find that rather small numbers, in the tens and low hundreds, can be written easily and elegantly but above this, things get clumsy, as shown by Figure 2.6. The need to add another symbol for each ten, hundred, or thousand means a rapid buildup of signs on the page (think of any number with a 99 at the end, for example). This was just as true for the Greek and Roman systems, which, in fact, were nearly identical to the Egyptian (and borrowed from it) but with different symbols. Fractions – which were central to Egyptian calculations – were expressed by a "mouth," meaning "1," above a number that represented the denominator. Thus, for the most part, only unit fractions (*1/n*) were used. For example, instead of ¾ the expression 1/2 + 1/4 was employed. The *Rhind Papyrus*

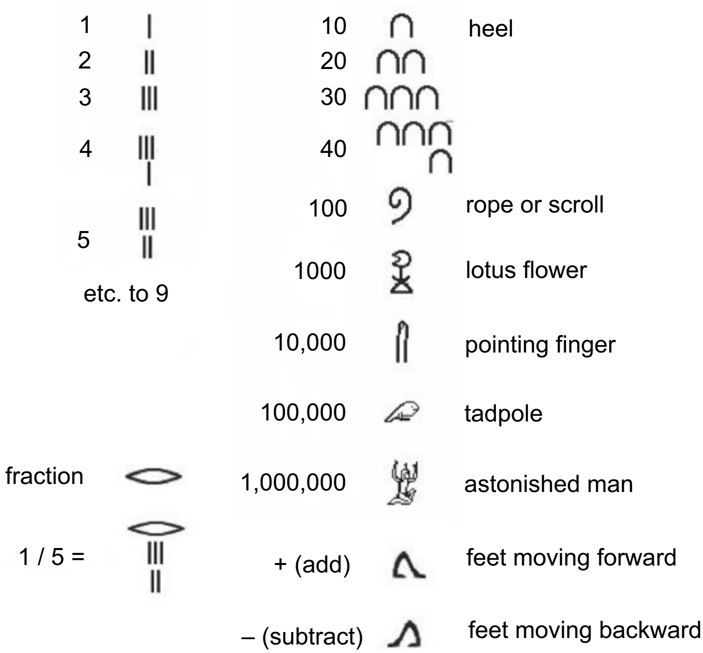

Figure 2.5 Ancient Egyptian number system, showing symbols and their literal meaning.

565

2,563

1/360

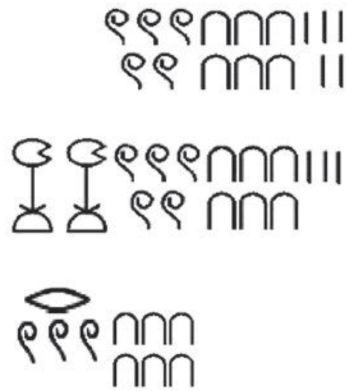

Figure 2.6 Writing numbers over 100 in the Egyptian system quickly became burdensome, making simple arithmetic laborious.

contains a unique table showing how $2/n$ fractions (n = odd numbers) can be broken down into $1/n$ equivalents (e.g. $2/3 = 1/2 + 1/6$).

Adding and subtracting were the two most common operations for the Egyptians (multiplication and division were carried out by repeated additions). Addition could be done by writing numbers in a vertical list, then combining each group of symbols at the bottom. These could then be put in final form by exchanging each cluster of ten for the next higher unit symbol (e.g. ten 100 symbols exchanged for a single 1,000 symbol). Subtraction works the same way, though by removal of symbols.

Problems given in the *Rhind* and *Moscow Papyrus* are meant to be practical. Many are word problems: in the *Rhind*, for example, the first six problems concern how to divide one, two, six, seven, eight, and nine loaves of bread among ten men. These then proceed to more complex arithmetic (mainly in fractions), algebra, and geometry. An example of an algebraic exercise is problem 24: a quantity plus 1/7 of it equals 19; what is the quantity? Such is elementary for modern algebra ($x + x/7 = 19$), but in ancient Egypt a more complicated, yet clever sequence of mathematical moves had to be made. The procedure starts by eliminating the fraction; the unknown quantity (x) is chosen as 7, which makes the left side of equation equal to 8, i.e. $7 + 7/7$. The next step is to determine the multiplier that must be used to turn 8 into 19. Using unit fractions, this turns out to be $2 + 1/4 + 1/8$. So the equation becomes:

$$8(2 + 1/4 + 1/8) = 16 + 2 + 1 = 19$$

Thus, $(7 + 7/7)$ must be multiplied by this same factor, $(2 + 1/4 + 1/8)$, to yield 19 and, as x, 7 must be multiplied by this factor:

$$7(2 + 1/4 + 1/8) = 14 + 7/4 + 7/8 = \mathbf{16 + 1/2 + 1/8} \text{ (final answer)}$$

We can see from this example, then, what an enormous innovation algebra must have been!

Exercises 56–60 in the *Rhind* are concerned with the dimensions of pyramids, and might be of some interest to the modern reader. Number 56 (Figure 2.7) asks how to find the *seked,* defined as the number of horizontal units per rise of one vertical unit (thus a measure of the pyramid's slope). Here is a translation of the problem:

> *Example of a pyramid with 360 in its ukha-thebet* [longest side] *and 250 in its peremus* [height]. *How will you teach me the seked of it?*
> *You are to take half of 360; it becomes 180.*
> *You are to reckon* [calculate] *with 250 to find 180.*
> *Answer: ½ + 1/5 + 1/50.*
> *A cubit being 7 palms, you are to multiply by 7.*
>
> *½ × 7 = 3 ½*
>
> *(1/5) × 7 = 1 + 1/3 + 1/15 (only unit fractions are allowed)*
>
> *(1/50) × 7 = 1/10 + 1/25*
>
> *Its seked is* [these three answers added together] *5 1/25 palms.*

The solution to this problem, therefore, is given as a fixed formula. The key calculation involves working "backward," we might say, from 250 to get 180, using only whole numbers and whole number fractions. As Figure 2.7 shows, finding the slope in the terms of a *seked*, though not how we define or determine slope today

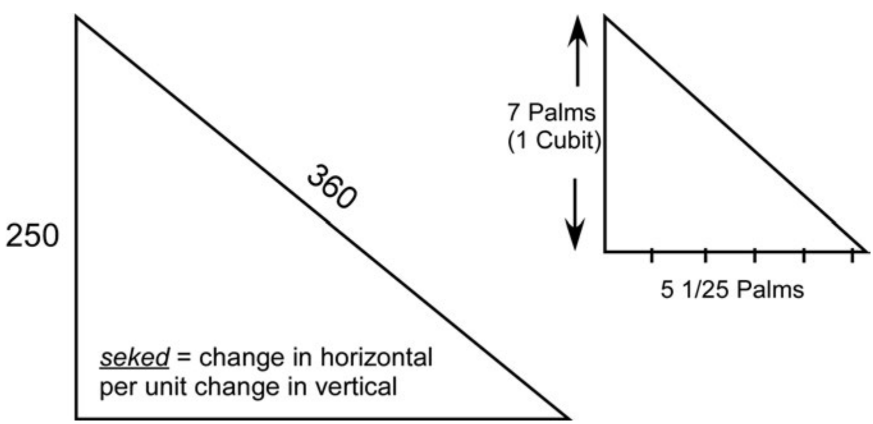

Figure 2.7 Problem 56 of the Rhind Papyrus, showing how to find the slope of a pyramid, or seked, knowing its height and length of its incline (hypotenuse). In this case, the Egyptians were interested in expressing the slope in terms of horizontal change per unit vertical change, a number that makes complete sense for those building such a structure.

(rise over run or vertical change over horizontal change), makes a good deal of sense if we are actually going to build a pyramid of a certain scale.

One other interesting point. How steep were the pyramids? Taking problem 56 as a possible standard of sorts, we can estimate this quickly. Since the *seked* represents the cotangent of the angle of slope, β, we can look up this angle and find that it is, in fact, quite steep, about 54.5°. Many of the Egyptian pyramids, it turns out, including those at Giza, are estimated to be in the range of 50°–54°.

These are only a few examples from the *Rhind* and *Moscow* papyri, but they give a good taste of what both contain. As valuable as these documents are, we should consider their limitations. If, in fact, they are what we believe them to be – instruction manuals – they almost surely offer a very limited idea of what Egyptian mathematics was like. Think of our own math textbooks today; how far are they from the level of work done by professional mathematicians? Greek writings tell us that thinkers like Pythagoras and Thales went to study in Egypt. These men would likely have learned little if practical calculations were all they found. It may be, then, that higher levels of mathematical thought were indeed attained. Perhaps the relevant works have not survived. Losses suffered by the burning of the Great Library at Alexandria may be even greater than we have believed.

The pyramids: technology on the grandest scale

"Soldiers, from these heights 40 centuries look down upon you," the young general pronounced, in sight of great pyramids at Giza, before leading his troops forward. While Napoleon won a victory that day, his mission to conquer Egypt and thereby gain Britain's overland trade route to India failed. The year was 1798, and Napoleon had brought 400 ships, 40,000 soldiers, and 167 scientists, engineers, and artists to Alexandria. Within ten days, his ships were routed by Admiral Horatio Nelson and soon after his soldiers suffered defeat and the plague. Yet his mission was a magnificent triumph. The *savants* (French scientists and philosophers) uncovered an invaluable treasure of relics, including the Rosetta Stone, and established the Institut d'Égypte, the first institution in the world devoted to Egypt's ancient culture.

Scholars from many fields have studied the pyramids of Egypt and have come to view them as scientific and technologic creations. Today, more than 100 pyramids are known. All were built on the west side of the Nile, linked with the setting of the sun and with death and the afterlife. The square-base form began to be used soon after 2700 B.C. and seems derived from the sun-god Ra, father of all pharaohs, who created himself out of a pyramidal mound of earth.

In the Old Kingdom, two types of limestone were used. The core of each pyramid was constructed with local rock, which is more porous and non-homogeneous. For the outermost layer, more dense and fine-grained stone from the Tura quarries was used. This limestone was polished to a high white sheen. At the top was a capstone of granite or basalt, probably covered with gold, silver, or electrum (a natural alloy of gold and silver). It is not hard to imagine that the great pyramids at Giza were a breathtaking sight in their time, visible from many miles as striking features of the landscape.

Slaves did not build the pyramids. Egyptian commoners, not chained Hebrews, built them. Hollywood has done a great disservice to historical truth. This unfortunate myth was taken to international heights in 1977, when Israeli Prime Minister Menachem Begin visited Egypt's National Museum in Cairo and stated, "We built the pyramids." Such is the stuff of ignorance and fantasy.

Pyramid workers were poorer citizens who took on such labor out of loyalty to the pharaoh and for the economic security such long-term work offered. These men were buried in tombs right at the sites of the sacred pyramids, oriented with their heads facing west, and surrounded by jars of provisions for the afterlife. Their remains show they suffered from arthritis and other wages of hard labor but were given medical treatment. No slave would have been given such concern. The consensus today is that about 20,000 to 30,000 workers were needed during the early stages of constructing the largest of the structures, the Great Pyramid of Khufu. As the pyramid grew taller, and as the buildings around it were completed, fewer workers were needed.

By any measure, erecting the pyramids was an enormous technical challenge that the Egyptians met with great skill. Simply consider the organization that was needed for all the thousands of people involved, whose tasks had to be met every day, for two decades or more. Consider the great array of jobs and skills: there had to be carpenters, metal forgers, metalworkers, quarry workers, stoneworkers, potters, bakers, brewers, butchers, water bearers, physicians, foremen, inspectors, as well as laborers. All of this effort had to be integrated, so that it progressed without major breakdowns. A veritable city in the vicinity of the construction site had to be built to house the workers. There had to be sufficient sanitation and medical care to prevent and control diseases like cholera, dysentery, and typhoid. The Egyptians knew that certain vegetables, notably onions, radishes, and garlic, were helpful in avoiding infectious illness, so these were provided in abundance.

Each pyramid, as a project, had to be expertly designed and carefully planned. Because of the time involved in construction, a pharaoh who decided on such a structure for his monument did so very early in his reign, appointing a committee with a construction manager (or master builder), an architect, and a chief engineer, among other technical experts. The master builder had plans drawn up by specialist scribes. He may also have had small-scale models created (one such model was found at the Pyramid of Amenemhet III at Dahshur). Sites were carefully chosen – those at Giza, for example, were on a limestone plateau at the edge of the desert, just above the Nile floodplain, offering safety from the yearly flood, good building material, and a relatively flat surface with excellent openness to the west. Orientation came next; pyramids needed to be aligned so that their four surfaces faced north, south, east, and west. The site for each pyramid was marked out, apparently using posts through which rope or string was run. Corners were drawn as precise right angles, determined perhaps by an instrument like a modified T- or A-square. The site was then leveled, both by the beveling of bedrock and use of masonry. A number of pyramids, including the Great Pyramid of Khufu, have bedrock cores, which greatly reduced the total number of stone blocks needed. Each pyramid lay at the center of a complex of buildings, including shrines, chapels, and temples, all of which were richly adorned and contained statues and hieroglyphic wall inscriptions of religious meaning.

In the quarries, blocks had to be marked out, then cut with specialized tools. Stoneworkers used copper chisels to quarry sandstone and limestone – the copper, mined as ore and smelted in the eastern desert and Sinai Peninsula, was especially hard, due to a high arsenic content. For granite and diorite, much harder tools were needed, and basalt and dolerite chisels were employed. Aswan granite from southern Egypt was especially prized for inner burial chambers, obelisks, and other monuments in the greater pyramid complex. One technique to free or split granite was to drill slots in the stone, pound wooden pegs into one side of each slot, then fill the rest of the slot with water: the pegs would absorb the water, swell, and split the stone. At every stage, the block would be inspected for quality control. Those that developed unwanted cracks would be rejected, left in place (there are examples of obelisks 30 m/100 ft long left in place because of such cracks).

How were blocks, even several at a time, and large statues transported on the ground? It is known they were put on sledges and dragged up to a kilometer or more. Until very recently, however, it wasn't known how this was specifically accomplished, since a sledge pulled with such weight on it would act as a bulldozer, pushing up a berm of sand and quickly coming to a halt. The question was solved, interestingly, by a combination of physics and art. Experiments performed by physicists at the University of Amsterdam in 2013 revealed that wetting the sand to a particular level caused microdroplets of water to bridge a certain percentage of sand grains (by capillary action). This effect greatly reduced friction between the sledge and the underlying sand surface, lowering the total force needed to move a particular weight by as much as half. The art side of the story is shown in Figure 2.8. This is a drawing of a portion of a wall painting in the tomb

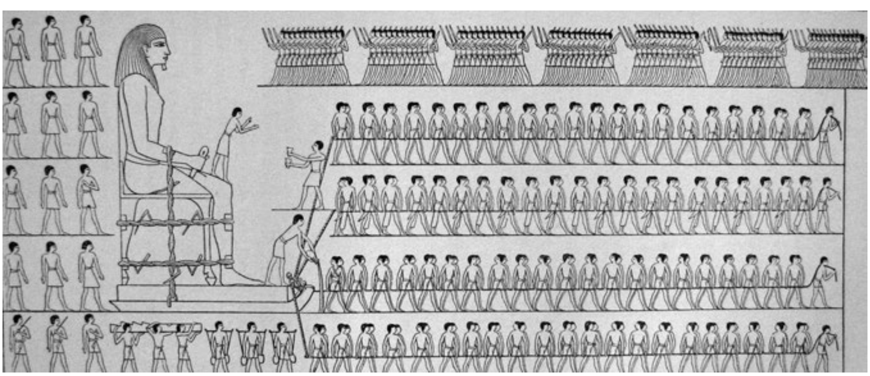

Figure 2.8 A line drawing of part of a wall painting in the tomb of Djehutihotep, showing workers pulling a sledge bearing a giant statue, bound in place by ropes. At the front end of the sledge is a worker pouring water onto the sand.

of Djehutihotep that gives us a portrait of workers hauling a giant statue bound by ropes to a sledge. Standing at the very front of the sledge is a worker pouring water on the sand. It was, in fact, this very painting that inspired the University of Amsterdam physicists to conceive their experiments, solving a truly ancient riddle.

The oldest pyramid is the Pyramid of Djoser, pharaoh of the 3rd Dynasty, designed as a step structure by the famous Imhotep, who was later deified as a patron of both architecture and medicine. The pyramid is considered the oldest large-scale, cut-stone structure in the world. It has six great steps and was originally about 62 m (205 ft) tall, 109 × 125 m (360 × 413 ft) at the base, made out of limestone from a local quarry. The burial chamber is granite from the quarries of Aswan, 900 km to the south. Such are simple facts that tell us a great deal: a massive system of engineering, technology, and labor organization was in place already by this time, 2650 B.C.

The Pyramid built for Khufu, pharaoh of the 4th Dynasty of the Old Kingdom, was erected over a 20-year period, between 2560 and 2540 B.C. It stands no less than 147 m (481 ft) in height – the tallest manmade structure in the world until the Eiffel Tower was built in 1889, more than 4,400 years later. Moreover, there are striking architectural aspects to its structure. The difference between the longest and shortest of the baselines is a mere 7.8 inches.[2] The faces of the structure all dip at slightly more than 51° and are slightly concave, tilting inward towards a central line, by about 1°, a unique aspect to this pyramid that remains unexplained. In total, the pyramid covers 5.3 hectares (13 acres). A common estimate that it contains 2.3 million blocks of limestone is wrong, based as it is on volume of the entire structure. The core of the pyramid is a large bedrock mass (other pyramids seem to have used rubble to fill large gaps and other spaces). As with the Djoser structure, the actual burial chamber was made of Aswan granite with individual blocks weighing up to 15–16 tons.

How were these enormous structures built? Today, we can safely say that aliens or divine acts were not required. Archeologists believe that ramps were used, built of mud brick and rubble and surfaced with a harder material. For the earliest step pyramids, like that of Djoser, individual ramps were built from each step to the next and then dismantled as the facing stone was added. The great pyramids at Giza (and afterward), however, likely used one or more ramps oriented perpendicular to each face with an inclination half or less than that of the pyramid itself (Figure 2.9). Sledges carrying blocks were pulled up the ramp by oxen and men. As the pyramid grew, the ramp(s) would be built upward and extended outward, so the angle could remain low enough for the sledges to be dragged without too much effort. As noted, these sledges were probably lubricated either by water or oil. Experiments have shown that 20 men could pull a 2.5 ton granite block up such a ramp.

Pyramids were not mere burial tombs. They were chambers of protection and transformation. They pointed upwards to the heavens and also downwards, like the rays of the sun. Within them and the smaller structures around them, the pharaoh, his wives and children, his attendants and priests, and even his pets, were placed for preservation. In the Egyptian religion, every living person had an interior essence or double, known as the *ka*, that would live on in the afterlife

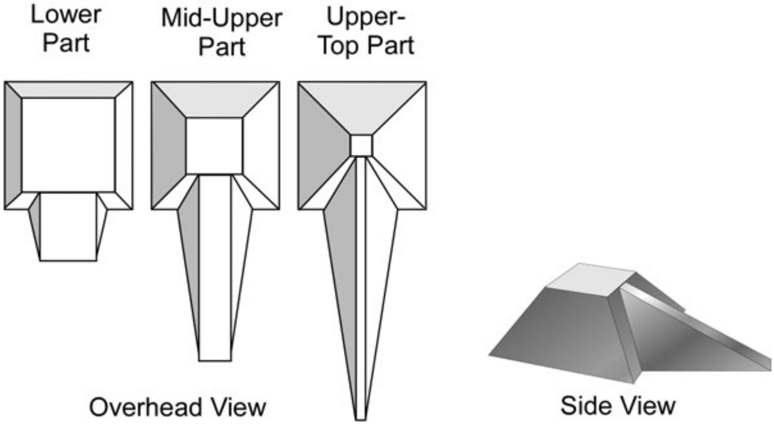

Figure 2.9 Many archeologists believe the pyramids were built using a sequence of ramps of constant slope. Early in the construction process, these were wide and low, to build the basal portion. They became progressively narrower and longer as higher parts were built. The slope was calculated based on the determined ability of a set number of workers to pull block-loaded sledges up an incline.

and needed a body to return to – therefore, the original flesh had to be protected against decay, hunger, and violence. Designers of pyramids put a sarcophagus chamber deep within the structure and ordered many of the interior passages to be plugged with large stones. It was important that the pharaoh's *ka* be safe and comfortable, with the food, drink, smells, clothes, furniture, ornaments, and services that he was used to. Without such care, pharaoh's power to bring good fortune to his people in the living world would be lost and disorder would descend upon them. When a pharaoh died he was transformed into Osiris, god of the dead, while the new pharaoh became Horus, god of the heavens. Thus the cycle of the sun's rise and setting, the Nile's rise and fall, the pattern for all life and death and return, was enacted.

Pyramid building lasted more than a thousand years, to about 1700 B.C., the Second Intermediate Period. This was when the Hyksos, a Semitic people from Asia, grew in numbers and influence through migration and local invasion, disrupting native traditions and eventually gaining supremacy in Upper Egypt. They introduced new technology, for example the chariot, a major innovation (despite its technical ability, Egypt had not yet used the wheel!). Only a century later, the Hyksos were driven out (ca. 1550 B.C.) and a new era of tomb-building began in the Valley of the Kings near Thebes (Luxor).

Why this new location, far to the south? One reason was that Thebes had become the home city of pharaohs by the late Middle Kingdom. Another reason, however, was that the Old Kingdom pyramids at Giza had been looted. Knowing this, the new pharaohs chose a site in an isolated desert wash, several kilometers from the Nile Valley, difficult to find and easy to guard. Instead of free-standing structures, tombs were bored directly into the limestone cliffs. Like the pyramids, a sequence of work was followed. Long, downward shafts ending in elaborate burial

Figure 2.10 A picture of the pyramids of Giza, including the Great Pyramid.

chambers were quarried by workers using bronze chisels and wooden hammers. Next came plasterers, who smoothed the walls with a mixture of clay, crushed limestone, and gypsum. Then draftsmen entered to mark out the walls for painting and inscriptions. Sculptors would next carve bas-relief images according to design, and painters would color them using six different shades, each with a symbolic meaning. During the entire process, lighting would be provided by clay pot lamps containing sesame oil or animal fat with salt to reduce the level of smoke.

In some ways, the pyramids and their successor tombs reveal the peak use of Egyptian science and technology. Their technological organization of labor, commanded by a higher class of planners, led Aristotle to write in his book *Metaphysics*: "the mathematical sciences originated in the neighborhood of Egypt, because there the priestly class was allowed leisure."

We may see the pyramids today as monuments to the dead, to death itself. Yet nothing should sway us from appreciating the technical genius involved in erecting these monuments, which express not arrogance and waste, as the Roman author Pliny the Elder said, but instead the power of religious beliefs matched with engineering mastery. If indeed the pyramids have now stood for 50 centuries and may stand for 50 more, they will continue to speak most clearly about this capability of the human mind to make inventive use of what nature provides.

Mummy factor

Mummies were the precious inhabitants of these monumental chambers, the pyramids. The word mummy is likely derived from the Persian *mummiya*, meaning "tar," used by early Islamic conquerors to describe the blackened appearance of the examples they frequently came across. In fact, many thousands of them existed. So many, it seems, that they were sold starting in the 12th century C.E. to apothecaries in Europe, where they were ground to powder and used as medicine.[3] In Victorian times, wealthy English tourists might bring one or two back to hold "unwrapping parties." It can only seem startling to us how little concern and respect existed in the past for these once-living bodies.

Egypt was by no means the only ancient culture to practice mummification. It was also done in Peru, Pakistan, and China and even took place by certain natural processes, such as freezing in ice and burial in peat bogs. And lest we forget, it has not been so rare in our own times, as the preserved bodies of Vladimir Lenin, Mao Zedong, Vietnamese leader Ho Chi Minh, North Korean leader Kim Il Sung, and Philippine leader Ferdinand Marcos show!

But Egypt was by far the most advanced and successful at it. Mummification was a sacred process that began in the Predynastic Period and continued to Greco-Roman times. No papyrus, wall inscription, or bas-relief tells us how it was done. Archeologists and Egyptologists have derived the method from a few ancient accounts of travelers but even more from physical and chemical analyses of mummies themselves. Indeed, a great deal of modern science has gone into such study. We know, beyond doubt, that the process involved knowledge of anatomy, surgery, chemistry, antisepsis, and some mineralogy as well. The Egyptians understood the body's interior, how it was put together, and also what certain chemicals, both natural and manmade, would do to it on the outside and inside.

A long process of experimentation occurred to find ways for preserving the precious remains within a sarcophagus. Data from the few remaining mummies of Old Kingdom age suggest that for some period of time the flesh was apparently removed and the bones subjected to a smoking process and, later, to complete drying in mineral salts and then sealing with resin. By the Middle Kingdom, however, priest-scientists had figured out that certain natural materials could stop decay pretty much altogether if the body was dehydrated. They achieved this using natron, a natural deposit that results from the evaporation of highly alkaline, sodium-rich lake waters – exactly like those in the Natron Valley of the northwestern Nile Delta. Natron consists of sodium carbonate/bicarbonate, with minor amounts of sodium chloride (table salt) and is an excellent drying agent and also a good antiseptic (it kills bacteria).

Once it was discovered that the flesh could be preserved, full mummification was put into practice. The process began with the body being washed with aromatic palm wine and then rinsed with water from the Nile. Next, various organs that were most vulnerable to immediate decay had to be removed – the Egyptians had clearly learned this through observation and experience over time. They began with the head. This most often involved removal of the brain by hooks that were inserted through the nose, rotated inward under pressure until they broke through into the skull cavity. Narrow, spoon-tipped rods then removed the soft tissue, and the skull was packed with linen, spices, and Nile mud. The eyes were closed and padded with linen. Then the mouth was cleansed and packed with linen soaked in preservative oil. Finally a resinous paste was spread over the face. Resins, such as terebinth, pine pitch, frankincense, and myrrh, are aromatic hydrocarbons secreted from certain plants. They are also antiseptics. The Egyptians used them very generously in preserving their corpses, heating the crystallized material (which has a low melting point) and pouring the molten result over the entire body or even, in some cases, filling it. Resin was able to seal the surface of bones, too.

When the head was complete, the viscera were next removed. An incision was made in the left side of the abdomen with a special obsidian knife, the "Ethiopian stone," and the liver, lungs, stomach, gallbladder, and intestines carefully removed. These were washed clean, packed with natron, then soaked in resin and put in special canopic jars (Figure 2.11), which were also placed in the burial chamber.

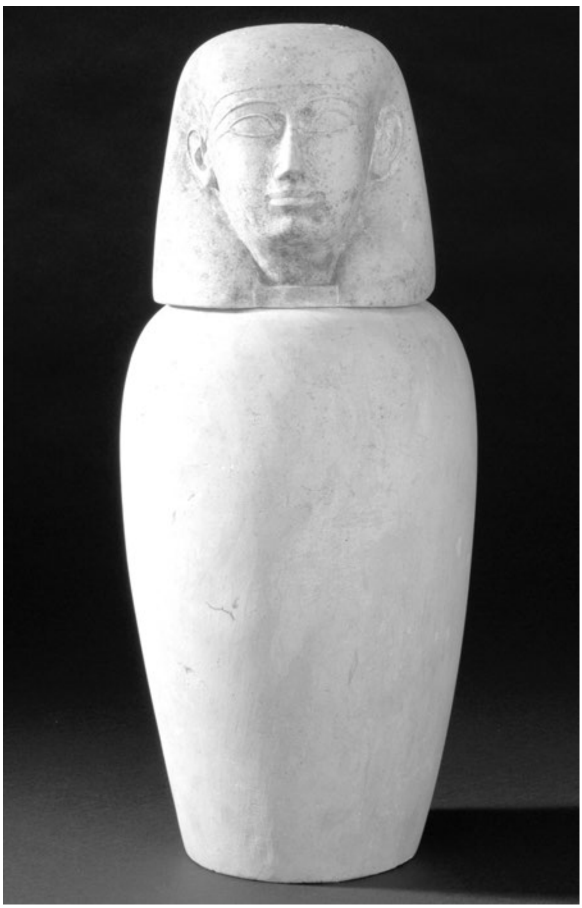

Figure 2.11 Canopic jar to store body organs. Courtesy of the Science Museum, London, Wellcome Images.

The heart, as the source of union between body and *ka*, was left inside the body, which was next covered and stuffed with natron to dry out all fluids. This typically required up to 40 days or more. Much later, by the Greek-Roman era, the organs were dried, covered in resin, wrapped and placed back inside the body. In either case, when it was complete, the body had a dark color and was very withered. It was then washed again with Nile water, filled with more natron or sawdust and aromatic resin. The skin was massaged and softened with milk, honey, and sweet smelling oils. Openings such as the nose, mouth, and ears were sealed with linen.

Before wrapping the entire body in linen, cosmetics and, in some cases, a wig, were added to create a more life-like appearance. These cosmetics included paints made from lapis lazuli (from Afghanaistan), ochre, malachite, and other substances, as well as gold leaf (for nobility and royalty). In the final step, the arms, legs, trunk, and head were all wrapped separately. Amulets and semi-precious gems, believed to keep away demons, were placed within the layers of wrapping to protect the body in the afterlife. Last of all, the wrapped body was coated in resin or a mixture of resin and bitumen. Early on, the face, head, and shoulders were often covered by a painted mask, meant to idealize the person's features. With time, this became an entire coffin, elaborately painted with necklace-type decorations, blessings and stories (of the deceased) in hieroglyphics, and other imagery. The entire effort of mummification required about 70 days.

By the time of the New Kingdom, when Egypt's population was perhaps three million, mummy making was both a sacred process and big business. Nobles could apparently order their coffins and sarcophagi ahead of time and contract priests and craftsmen for the total effort. Writings testify to competition among the wealthy regarding extravagant banquets, pleasure gardens, and possessions, and it isn't difficult to imagine something similar regarding their upcoming trip to the afterlife.

The chemistry of mummies has proven a rich area of study. Mass spectrograph analyses show that the Egyptians used mainly terebinth, pine-pitch, and pistachio resins, rather than frankincense and myrrh, which we can interpret as being too expensive for consistent use in mummification. We also now know that the natron used by the Egyptians fortunately contained borate, a particularly strong killer of bacteria and fungus, that significantly aided preservation. One very interesting result has come from analysis of mummy hair: this shows a kind of "styling gel" was used in cases where the person's original hair was still in good condition, showing an effort to preserve some aspects of the living individual.

Medicine: pinnacle of Egyptian science

No other area of Egyptian science seems to have been so advanced and specialized at so early a date as medicine. Nearly half of all doctors whose names we know are from the Old Kingdom. This excellence led Homer in the *Odyssey* to declare that "no one else knows medicine as they do, Egyptian heirs of Paian, the healing god."

As with mathematics, a great deal of what we know about medical practice comes from a small group of surviving papyri, most of which are instructional in nature. Two of these, the *Edwin Smith* and *Ebers* papyri, are especially important, due to their state of preservation, length, and contents. Though they date from the New Kingdom, their language suggests they are copies of texts written in the Old Kingdom. The *Edwin Smith Papyrus* is a kind of textbook that describes surgical techniques for traumatic injuries, such as might be suffered in war or dangerous work (quarries, mines, building sites). The *Ebers Papyrus* is a listing of treatments and remedies for more than 80 conditions, ranging from migraine and baldness to enlarged prostate. The longest of all the medical papyri at 110 pages, it is actually a group of works assembled in no particular order, like a sourcebook. The scribe, however, has numbered the remedies, making the text easier to use by a teacher or student.

What ailments did the Egyptians suffer from? There were many. We know this due to field of paleopathology (study of diseases in the past), which has been able to utilize advanced medical imaging, biochemical and DNA analysis, genetic testing, and other diagnostic tools. By 2010, more than 3,000 mummies had been studied to varying degrees using these tools. As a result, a far richer, more nuanced, and accurate picture of disease and injury in ancient Egypt has now emerged.

Given life along a major river, in marshy floodplain and deltaic areas, we would expect that parasites were a problem. Among the most common, today as in ancient times, was the bilharzia worm that causes schistosomiasis. Roundworm, tapeworm, Guinea worm, and unidentified intestinal worms all have been found in mummy remains. Water from the Nile apparently resulted in eye infections, as did dust and sand from the Sahara. But even more widespread in the delta region and lower Egypt was malaria. This has been proven by immunological and DNA tests on skin, muscle, and bone samples from Predynastic mummies (~3500 B.C.), as well as from pharaohs and nobles who lived in the New Kingdom. We now know, for example, that the famous boy pharaoh, Tutankhamen (King Tut), who died at age 19 around 1324 B.C., was quite frail and must have led a constrained life, stricken as he was by malaria and a bone disorder. Malaria, then, was likely endemic. And when we think of the style of irrigation the Egyptians used, which created large areas of standing, stagnant water for up to a month or more, we can see why.

So we begin to suspect that the people of the Nile did not inhabit paradise. Deserts could protect them from invading armies but not from parasites and microbes. Nor could relative isolation defend them against the effects of incest among the royal family and the preference of priests and nobles for red meat and pork. Egyptians, it has been found, also suffered from heart disease including high blood pressure and angina, varicose veins, atherosclerosis, gout, diabetes, aneurysms, cancer (several or more kinds), tuberculosis, pneumonia, emphysema, bronchitis, liver disease (unspecified) and, less often, polio, smallpox, meningitis, tetanus, hydrocephalus, and rare diseases like Hand-Schuller-Christian disease. Given the amount of ailments related to the heart and circulatory system, stroke was also probably fairly common, at least in those who reached a more advanced age, e.g. 40 or more. That conditions like atherosclerosis were common in people still in their 30s can only seem striking to us today. Also diagnosed from many mummies are physical problems such as hernia, arthritis, scoliosis, abscesses, obesity, and kidney stones. Constipation and diarrhea were both common, based on the many prescribed treatments for these ailments. Children appear to have had urinary tract infections and other urological disorders fairly often, given the many treatments prescribed for "water to pass" from them.

In addition to all these known illnesses, the medical papyri name many conditions that can't be clearly identified or identified at all. An example from the *Ebers Papyrus* prescribes the use of oil from the Ricinus plant (source of castor oil) to treat someone "with the *wehau*-skin disease, affected with *itjetjet* and *hewau*, which is painful." There is no way to know what exactly is meant here; painful skin conditions are associated with many illnesses, as varied as smallpox and psoriasis. We can assume, however, that there were even more medical problems in ancient Egypt than now known.

As if this were not enough, people also had to deal with dental problems of every type and level of severity. Mummies of children and adults make it clear that periodontal (gum) disease, as well as cavities and abscesses, were present in as much as 18% of the population. In other words, a good part of this society walked around each day in some degree of pain. Again, what could have led to all these ailments?

The short answer is: lifestyle and diet (sound familiar?). Most mummies that have been studied with modern methods represent people from the upper classes of society. These people came to lead luxurious lives, consuming large amounts of liquor and sweets, as well as fatty meats, lots of them – ducks and geese, for example, also pork, lamb, some beef, veal, and various vegetable oils. Meats rich in fat appear to have been prized for taste as well as status. Wall inscriptions describing banquets in the Old and Middle Kingdoms tell us they were enthusiastic affairs, with vast amounts of food and drink consumed and hosts defining success on the basis of how many guests ended up drunk or sick. Large homes were furnished with "beer halls," where drinking and table gaming were almost daily activities. On top of this, medical treatment for a number of ailments specified ingestion of animal fat, including being bathed in the smoke of burning grease (e.g. in the *Kahun Papyrus*, the treatment for "a woman pained in her vulva, and all her limbs" is to "let her eat fat until she is well"). Servants performed nearly all manual work, so there was little opportunity for exercise. Finally, many people of all classes had weakened or compromised immune systems due to lingering infection and long-term inflammation. After agriculture became the staple source of food, people lived in close quarters, making infectious and contagious diseases more easily spread, increasing exposure to animals who could carry pathogens, and also to less-than-ideal sanitary conditions.

Earlier in this book we spoke of the Neolithic or Agricultural Revolution as one of the key events in human history. Was it entirely a good thing? For many years, this was the standard interpretation. Yet, since the 1980s, researchers aided by multidisciplinary study of ancient human remains have changed their thinking about this. Agriculture did improve security of the food supply, helping create a population explosion, but the hunter-gatherer diet that *homo sapiens* followed for more than 150,000 years is now thought to have been much healthier. This is because it was centered on both leaner meats (e.g. free-roaming herbivores and carnivores) and a greater variety of nuts, fruits, and other vegetal matter. With the advent of systematic farming, populations came to rely on a small number of grains able to provide only part of the nutritional needs for good health (think of surviving on bread and beer, with a little fruit and meat now and then). Studies of adult stature for ancient Egyptians show a rapid rise after the start of intensive farming (~3750 B.C.), then a peaking for both men and women in the Early Old Kingdom period, followed by a major drop by the end of the Old Kingdom. Given that there were no major migrations into the Nile Valley during this time – that we are dealing with a single population – this data implies an overall decline in public health. Adult stature, we might note, primarily reflects genetics influenced by childhood nutrition (North Koreans, who have suffered multiple famines since the 1980s, are on average 7.4 cm, or 3 inches, shorter than South Koreans).

Medical practice: what was done?

Taking all of this information into account, we might be tempted to wonder how Egyptian society ever survived, let alone *prospered* as a great civilization. But is our own civilization so different? The question is not just how ill a society may be but how it produces illness and how it cares for the sick.

In ancient Egypt, we can guess that physicians were quite numerous and busy and were considered effective. Recall that most of the medical papyri are instructional in nature. This suggests these were the most abundant texts of the profession (abundance favors preservation), which recommends the idea that many doctors were in training at any one time and that the profession attracted many apprentices. We know that among professional physicians there was a hierarchy, with those treating the royal family at the top, next those who worked on the nobility, priests, and scribes, and then the more "lay" doctors who tended to the mass of the people. There were also master physicians, senior doctors, journeymen, and specialists. Many physicians, particularly for the royal family and the nobility, focused on certain parts of the body, e.g. the eyes, the head, the belly, the hands and feet, genital areas. Others became particularly expert in certain types of practice, such as surgery, childbirth, or pharmacology. Surgeons, meanwhile, could focus their work on traumatic injuries, on bone-related problems, amputations, or lesions to the skin. Circumcision was practiced, but we don't really know how widely. Some images, such as stone friezes at the Tomb of Ankhmahor (also known as the "Physician's Tomb"), show what appear to be circumcision and possibly hernia operations (Figure 2.12). This suggests such procedures were far from rare.

Prosthetics were also made – there is the remarkable example of artificial toes (two are known), one made from wood and leather, the other of linen soaked in glue and coated with plaster. These are the oldest prostheses known, from any part of the world. Both toes have been tested by individuals missing their right toes and found to operate well as true artificial digits. A photograph of one of these toes (Figure 2.13), which came from a female mummy older than 600 B.C., is striking.

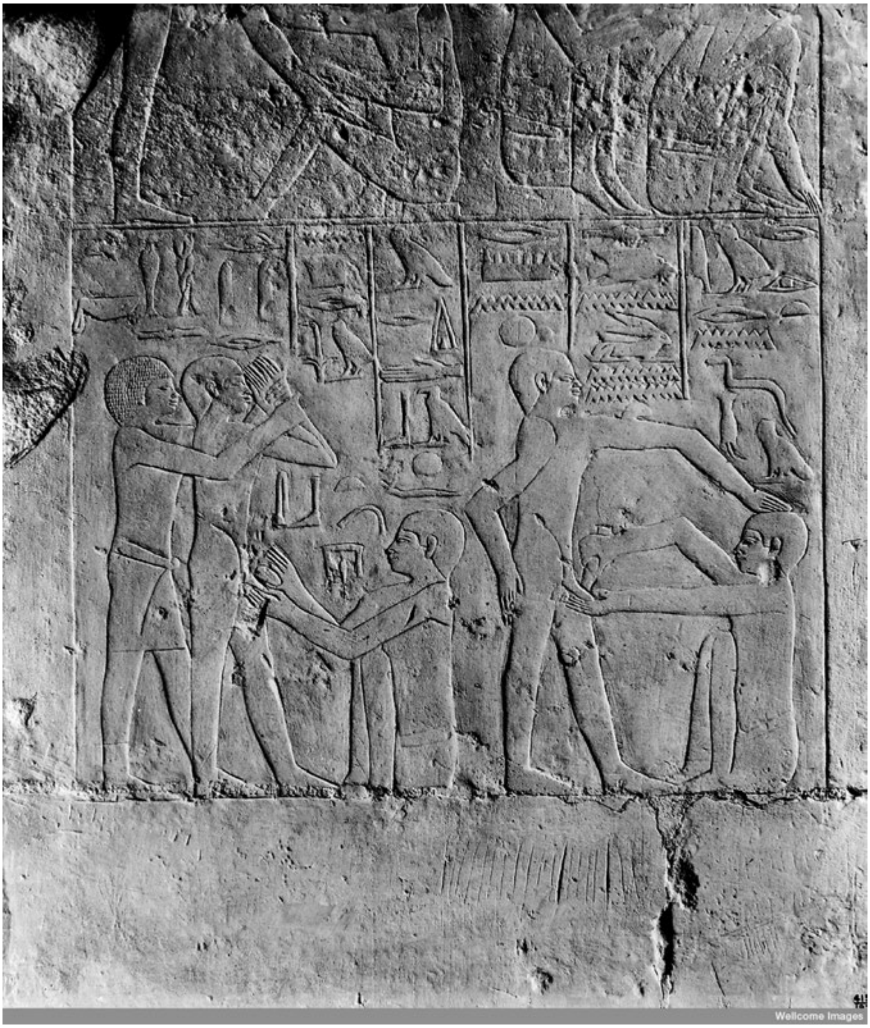

Figure 2.12 Part of a frieze from the Tomb of Ankhmahor in Saqqara, also known as the "Physician's Tomb." This image shows a circumcision in progress, with the accompanying hieroglyphics warning: "Don't let him faint!". Courtesy of Wellcome Library, London.

That it is both highly lifelike and also made to be adjustable in some part implies that this is no isolated example but came from a craftsman who had worked out needed details through experience. We are led to wonder if injuries to the feet, and related infections, were particularly common. But again, we don't know how often this was done. Replacement limbs on mummies are not at all rare, but it doesn't seem as if they were used in life. They are often crude and were probably placed with the body to simulate a full physical form, a lack of disfigurement, under the linen wrapping. Physicians probably did not make these nor the toes noted above.

Figure 2.13 A prosthetic toe taken from a mummy dated at before 600 B.C. Two such toes are known and appear to have been used while their owners were alive. These are the oldest prostheses thus far known.

Some doctors were certainly scribes. All of them, at least the non-charlatans, were literate, indeed among the most highly educated members of society. They were, therefore, generally chosen from among the upper strata of society, although it appears that they were not all priests, particularly from the later part of the Middle Kingdom on. In sum, the medical profession was large, well-organized, diverse, and busy. This leads to the question of how they were trained.

Doctors were educated in a system of schools that were part of a key institution known as the House of Life. There were at least seven of these houses, located in major cities like Abydos, Heliopolis, Thebes, and Memphis. They were much more than medical schools. Scribes, who were the mathematicians and authors and record keepers of Egypt, were also trained here. Each House of Life was attached to a great temple and acted as a center of knowledge and practice in a number of areas, including mathematics, architecture, medicine, literacy, geography, and law. Its overall purpose was to create and record knowledge that would enhance political and social order in obedience to the rules of the gods and the cosmos. Again, no distinction between knowledge and religion existed; there were rituals, verbal and gestural, associated with every branch of science.

Based on the medical papyri, in fact, students followed a curriculum based on memorization of treatments, or "laws," written down by earlier physicians. Some degree of actual hands-on practice must have existed as well, but it was the written word that dominated. This was also true for the required knowledge of botany – the preparation using healing herbs of medicines, salves, ointments.

Herbal medicines, plus drugs made from animal and mineral substances as well as vegetal ones, constituted the major form of treatment. Much experimentation obviously went into this domain at some early point. But by the later part of the Old Kingdom, it seems students followed written recipes and routines of application that had been set down centuries earlier. These were undoubtedly amended over time to some degree, but it does seem that the "ancient ways" had great authority in the Middle and New Kingdoms.

What view of the human body did Egyptian medicine have? Basically, the body was a system of channels, called *metu*, like a great river system with many tributaries. These conducted essential fluids – air, blood, lymph, mucus, sperm, urine, feces, tears, saliva – through the body and linked together all its parts. The heart was the center; many of the *metu* were thought to flow to or through it. Curiously, the brain seems not to have been valued very highly (recall that it was withdrawn and discarded during mummification). The overall image resembled the Nile, with its many flows and its great delta; this frame for human anatomy and physiology, therefore, connected the body with the cosmic order. Meanwhile, the distribution and function of the *metu* are discussed in the *Ebers Papyrus* (paragraphs 854 and 856), partially repeated in the *Berlin Papyrus* (163), and are given in terms of their destinations: "There are four *metu* for his (a man's) two ears" (*Ebers*, 854f); "There are four *metu* for the lungs and the spleen; it is they that give the fluid and the breath" (*Ebers*, 854m); "Twelve [should be "Twenty-two"] *metu* are in him for his heart; it is they that give the breath to each place in his body" (*Ebers* 856b). The body in its native state was considered healthy. Illness came from the effects of some foreign substance or influence. Worms, snakes, blows, and poisons were obviously among these. But so were spirits and demons; these were felt to be responsible for ailments that had no external marks or manifestation.

When did blood flow begin?

The core idea of flow and return within the body is nearly as ancient as medicine itself. If the Egyptians saw this idea as central, so did the physicians of early India and China. The perception that forms of flow took place within the body – that bodies of people and animals held within them dynamic movements of fluid and force – was surely known or suspected from hunting and war at a time far earlier than when the first blocks of any civilization were laid. What the scientific cultures of these civilizations did, however, was to construct explanatory systems for this dynamism, systems that had both aspects of empirical observation and spiritual or religious elements closely merged. Proper and unbroken flows, of liquids, nutrients, energies, influences, were key in each of these systems.

It was indeed the model that William Harvey developed more fully, from experimental results, in his famous work *De Motu cordis* ("On the Motion of the Heart and Blood," 1628), where he proposes that the blood "might rather have a certain movement, as it were, in a circle." This was radical at the time for Europe. Harvey's contemporaries believed that the blood was constantly being consumed by tissues and locally produced from digested food. It moved through the body, certainly, but not so globally as in ancient systems of understanding, more in a regional sense, centered on organs. Could we say, then, that Harvey actually "re-discovered" a concept with an ancient legacy? Was he possibly influenced by other, earlier thinkers?

It is interesting that a famous 13th century Muslim physician, Ibn al-Nafis, also wrote of the blood's circulation and did so in a commentary on the great Avicenna, who had a major impact on medieval European medicine. Born in Damascus, Al-Nafis spent most of his life in Cairo and was the Sultan's personal physician. None of this can take away from Harvey's enormous contribution. But it tells us that this contribution did not take place in a historical vacuum. It cannot be so easily said that the idea of the body as a site of fluid movement, with the heart at the core of such movement, was a European discovery.

We come, finally, to the matter of diagnosis and treatment. Both of these focused on symptoms – on reading the signs of illness and addressing them. As we've said, the theory of disease was a simple one, based on the identification of foreign creatures, substances, or spirits. Pretty much every ailment that did not require surgery was treated with a medicinal recipe. Medicines are directed to be taken internally as pills, infusions and decoctions but also in some cases externally as ointments, salves, lotions, and so on. Here are some examples from the *Ebers Papyrus*.

For schistosomiasis:

> [A] remedy, useful as something prepared for the belly: reeds, 1 part; *shames*-plant, 1 part. Grind fine, cook with honey, [to be] eaten by a man in whose belly [are] *hereret* worms. It is the *aaa* that created them. Not killed by any [other] remedy.

For migraine (which occurs on one side of the head):

> Another [remedy] for suffering in half the head. The skull of a catfish, fried in oil. Anoint the head therewith.

For polyuria (over-production of urine, e.g. due to diabetes mellitus):

> Another remedy that reduces urine when it is [too] plentiful: groats of wheat, 1/8; desert dates, 1/8; Nubian ochre, 1/32; water, 1/64. Soak in rainwater, strain, to be taken for four days.

The full range of materials that go into the making of such medicines is nothing short of spectacular. Over a thousand substances were employed, from every part of the natural environment. Hundreds of plants, including not just herbs but trees, flowers, thorns, grains, fruits, wood, resin, and seeds were used. So were many dozens of minerals, from alabaster, hematite, and quartz to granite, sulfur, and copper. Water from the Nile was of course included. But so were the hair, blood, ears, feathers, claws, bones, and other parts of many animals – lions, hippos, snakes, mice, vultures, dogs, scorpions, wasps, and tarantulas. Artificial substances, like wax, mineral salts, syrups, and balms, are also included in medicinal recipes. All of these materials were utilized as ingredients in combinations meant to address specific ailments. Many ailments had more than one remedy; some had many. Combinations vary from one or two ingredients to more than a dozen; components from the animal, vegetable, and mineral worlds all included. At times, they seem odd, as with this remedy for burns: "onions, red-lead, fruit of the *am* tree; crush, rub in copper splinters, make into one consistency, and apply as a plaster." At other times, they verge on the absurd, as in *Ebers* 262, where a remedy to stimulate urination prescribes "an old book, boiled in oil" to be rubbed on the belly.

Such recipes make sense, however, in light of the Egyptian belief that every substance was the manifestation of some spirit, with health an endless struggle for balance between good and evil. It isn't surprising, then, that the entire biological and physical world of Egypt itself was called upon to heal the sick, to reestablish order within the body in concert with that in nature.

Herbs in the Ebers Papyrus

A selection of medicinal herbs and the conditions for which they were used, as mentioned in the *Ebers Papyrus*, is the following:

- Acacia – eases diarrhea and internal bleeding; treats skin diseases
- Aloe vera – worms, headaches, chest pains, burns, skin disease, and allergies
- Caraway – soothes flatulence, digestive, breath freshener
- Common juniper tree – digestive, soothes chest pains, soothes stomach cramps
- Fenugreek – respiratory disorders, cleanses stomach, calms liver, reduces swelling
- Frankincense – throat and larynx infections, stops bleeding, asthma, vomiting
- Garlic – gives vitality, aids digestion, mild laxative, shrinks hemorrhoids, rids body of "spirits" (note: pyramid workers were given garlic daily to provide the vitality and strength to carry on and perform well)
- Henna – astringent, stops diarrhea, closes open wounds
- Honey – widely used, a natural antibiotic, to dress wounds, as base for healing unguents
- Mint – soothes flatulence, aids digestion, stops vomiting, breath freshener
- Mustard – induces vomiting, relieves chest pains

- Myrrh – stops diarrhea, relieves headaches, soothes gums, toothaches, backaches
- Onion – diuretic, prevents colds, soothes sciatica, relieves pains
- Tamarind – laxative
- Turmeric – closes open wounds (also was used to dye skin and cloth)

Reading through this list, we might suspect that some of these herbs and substances are used for similar purposes today. We would be entirely correct in this. Examples include: aloe vera for use in skin diseases and allergies; turmeric as an aid to close open wounds; onion as a diuretic; garlic as a purgative; fenugreek as a means of calming the stomach and liver; honey as an antiseptic; mint as a breath freshener; and so on.

What of surgery, then? The *Edwin Smith Papyrus* is unique among the medical texts for concentrating on surgical treatment for traumatic wounds and injuries in the upper part of the body. From other works, from mummies, and from actual physician tools like copper needles, it's obvious that Egyptian doctors were skilled in making splints, reconnecting broken bones, and suturing tissues. But the Edwin Smith text reaches well beyond this, into the lands of neurosurgery. Besides being the oldest surgical treatise known, it holds, for instance, the first descriptions of the meninges, cranial pulsations, cranial suturing, impact of brain injuries on the functioning of the lower limbs, and more. Each of its 48 cases is given one of three judgments: treatable with favorable result, treatable with uncertain result, and untreatable. One very interesting feature of each case instruction is its demand that the physician pronounce to the patient what the condition is and whether he will treat it or not. Here, for example, is case 2:

> *Title*: Instructions concerning a [gaping] wound [in his head], penetrating to the bone.
> *Examination*: If thou examines a man having a [gaping] wound [in] his [head], penetrating to the bone, thou shouldst lay thy hand upon it [and thou shouldest] palpate his wound. If thou findest his skull [uninjured, not hav] ing a perforation in it . . .
> *Diagnosis*: Thou shouldst say regarding [him]: "One hav[ing a gaping wou]nd in his head. An ailment which I will treat."
> *Treatment*: [Thou] shouldst bind fresh meat upon it the first day; thou shouldst apply for him two strips of linen, and treat afterward with grease, honey, and lint every day until he recovers.

It isn't clear whether the spoken words were meant to have an incantatory purpose (declaring to the god Sekhmet, goddess of healing) or to calm the patient. Either way, use of the spoken word as part of the process of diagnosis sets an early precedent.

So did the medical profession's handling of fertility, pregnancy, infant health, and contraception. Herbal formulas covering these areas are given in the Ebers, Berlin, Kahun, and Carlsberg papyri, showing that this domain was of no small concern. Egyptians greatly favored having children, who were considered a blessing because they would become caregivers of their ageing parents, a crucial element in social stability. Moreover, infant mortality was high, and having a large family also showed the favor of the gods. The Greeks, who often killed their deformed and unwanted infants by exposure, were stunned to see that efforts were made to save all children in Egypt, regardless of condition and gender. Yet birth control and family planning were also practiced. It was quite possible to have too many children; Egyptians understood the economic realities of a growing family. Physicians had the means to prevent pregnancy as well as to improve its chances and its progress.

To regulate a woman's menstruation so that she might be more fertile, a douche was prescribed of garlic and wine. If this failed, a second mixture of fennel, wonderfruit, honey, and sweet beer was to be applied for four days. Tests that cover fertility, pregnancy, and the gender of a fetus take up a sizeable part of the Kahun, Berlin, and Carlsberg documents. The most famous of these is from the Berlin text, and goes like this:

> Emmer and barley the lady should moisten with her urine every day . . . in two bags. If they all grow, she will bear a child. If the barley grows, it means a male. If the emmer grows, it means a female. If they do not grow, she will not bear a child.

The procedure sounds intriguing enough, since, like some modern pregnancy tests, it is based on a woman's urine. Use of the urine as an indicator would likely have existed very early on, given the common change in odor during the early stages of pregnancy. This is largely due to the hormone human chorionic gonadotropin (hCG), found in the blood and urine. The Egyptians, however, may have been the only ancient people to recognize that the change in smell meant a change in chemistry that could be tested.

In fact, the procedure noted above has been given a trial in a modern laboratory. The results showed that urine samples from non-pregnant women did indeed prevent any germination of the barley and emmer, though so did about half of the urine samples from pregnant women. No ability of the test to predict an unborn child's gender was seen. So the test largely succeeded in determining pregnancy and failed in its other claims. Another method used by the Egyptians was to sit the woman on a floor covered with beer mash, which would have a strong, bitter odor, and see if she vomits. This may sound absurd or silly only to those who haven't themselves undergone a pregnancy. During the first three months, "morning sickness" and nausea are very common experiences.

Doctors did not help with the birth process – two "midwives" attended the pregnant woman, who squatted on two large bricks or a seatless chair – but they did provide remedies when labor was late. To "loosen" a child in the womb, the *Ebers Papyrus* gives several treatments, e.g. sea-salt; grain-of-wheat; a female reed, ground into a plaster and applied to the abdomen; or, more simply, a mixture of equal parts fresh salt and honey, strained and taken for one day. Once a child was born, "Nothing accords more with natural law than one's mother milk," the *Ebers Papyrus* says. Most infants were breast fed for three years, and the Ebers even offers a stimulant for milk production in new mothers: "spine of the Nile perch, fried in oil/fat; anoint her spine therewith." Such methods haven't (yet?) been subjected to laboratory testing.

Yet contraceptives in the ancient texts are thought by researchers today to have been effective. A number of the recipes include ingredients from the acacia tree (bark, gum/sap, small amounts of wood), which have proven spermicidal effects. How, we might ask, were such effects discovered? Biomimicry might provide an answer: early herders perhaps noticed that female animals failed to get pregnant if they had grazed on this plant. To disperse the "active principle" of a contraceptive, physicians employed honey, an excellent choice given its acidity (pH < 5), ability to coat interior surfaces, its power to absorb moisture, and its pleasing aroma. One of the simplest contraceptive formula involved soaking a small section of linen in honey that had been steeped in acacia "spikes," a forerunner of today's diaphragm or sponge. Other ingredients, such as sour milk and natron, also had sperm-denying capabilities, on the one hand by increased acidity and the other by desiccation combined with a high pH.

In the end, Egyptian medicine shows a long-term historical pattern of rise and maturation, followed by stagnation. The many advances of the Old Kingdom became authoritative by the Middle Kingdom and thereafter were treated as gospel. "Wisdom of the ancients" was a powerful idea in Egypt, as it was in many pre-modern civilizations. While this idea may seem opposite to modern scientific progress, which demands continual improvement over the past, we might keep in mind that something similar occurred in the earlier stages of Egyptian medicine, when recipes and techniques were first conceived and tried out. While we have no detailed record of this process, we see the result: during the first 700 years after writing was invented, physicians created a systematic domain of medical knowledge and practice and wrote down this knowledge so it could be taught and passed on. A thousand years later, by the New Kingdom and after, spells and incantations had become common. This didn't mean the old remedies were abandoned. But medicine, with its public face, responded to social change, and under the New Kingdom, Egyptian society became more diverse, with many immigrants from societies where chants and spells (e.g. to get rid of ghosts or demons) were dominant.

By the New Kingdom, Egyptian physicians were called upon by many rulers in surrounding kingdoms. Methods and remedies, though at times only partially effective or even ineffective, were still far more advanced than what the Greeks and Romans would later practice using the theory of "humors," with bleeding and purging as key therapies. Indeed, we should pause here. Five thousand years after physicians in Memphis were using the antibiotic capabilities of honey and acacia to treat internal bleeding, George Washington was having his veins opened for an infection of the epiglottis. In 12 hours, 35% of the blood in his body had been taken, hastening his death the next day.

Rosetta Stone: power of the word

While knocking down an old wall to clear space for a new fort, one of Napoleon's officers, Captain Pierre-François Bouchard, noticed a black stone slab with different types of writing on it. The stone was very hard and had been used as part of a wall for the old fortress. Knowing that a main goal of the Egypt expedition was to collect material for scientific analysis, Bouchard consulted with his commanding officer, then had it cleaned off, wrapped, and set aside for safekeeping. It was 1799, and Bouchard was working near the town of Rashid, meaning "little rose" or Rosette/Rosetta, in the northeastern Nile Delta.

The decision to keep the stone, of course, was epochal. Napoleon himself inspected it more than once. Soon, however, with the French defeated, it came into British hands, was transferred to the British Museum, and was then presented before the Society of Antiquaries of London in 1802. The society saw the writings were in Greek and two forms of the ancient Egyptian language, hieroglyphics and what was called Demotic ("of the people"). In the spirit of scientific internationalism, the society made prints of the inscriptions and sent them to scholars throughout Europe. It would take a half-century before the stone was fully decoded and the first understanding of hieroglyphics in more than 1,500 years was achieved, opening up 3,000 years of a unique civilization to the modern eye.

The Rosetta Stone is a stele 114 cm (45 inches) tall, 72 cm (28.5 in) wide, and 28 cm (11 in) thick. Stele were upright slabs inscribed or sculpted with various messages, including decrees and laws. On the stone is a declaration by priest-scribes at Memphis in 196 B.C. of the divine cult of the new ruler, Ptolemy V. Figure 2.14 shows the three different writings, hieroglyphics on top, demotic next, and Greek below. The hieroglyphic text is the most damaged, with only 14 preserved lines, compared to 32 lines in demotic, and 54 in Greek. Visually, the hieroglyphics are elegant and balanced, the demotic curvilinear and less regular, and the Greek blocky and crude. A different person, therefore, inscribed each language. The vertical arrangement and level of craft are probably meaningful.

Hieroglyphics were one of the very first forms of writing, dating from around 3200–3000 B.C. and represent the critical transition from an all oral society to a textual one. It is interesting, and no coincidence, that the same social class that became literate, the priests and scribes, were also the ones responsible for learning and applying knowledge of the natural world. Hieroglyphic writing established a connection with this world, as nearly all of its forms are animals, insects, plants, water, and parts of the human body.

But by the time the Rosetta Stone was inscribed, 3,000 years after hieroglyphics had been invented, the writing system had become hugely burdensome and esoteric. The number of signs had grown from about 800 to nearly 5,000. The system was now a highly formal craft more than a domain of literacy, known to a tiny few but still carrying a sacred charge. Starting in the 7th century B.C., the new demotic script took over for literary, legal, and other papyrus documents, becoming the core of Egyptian literacy. These realities, then, help explain the top two sections of the Rosetta Stone, as well as why they are both there. Greek, meanwhile, was the lingua franca of the eastern Mediterranean and had been so since Alexander the Great conquered the region and installed his generals as local kings (4th century B.C.). Greek, however, was used to write on papyri and parchment, particularly in Egypt, and not for inscriptions, thus its clumsy character on the Rosetta Stone.

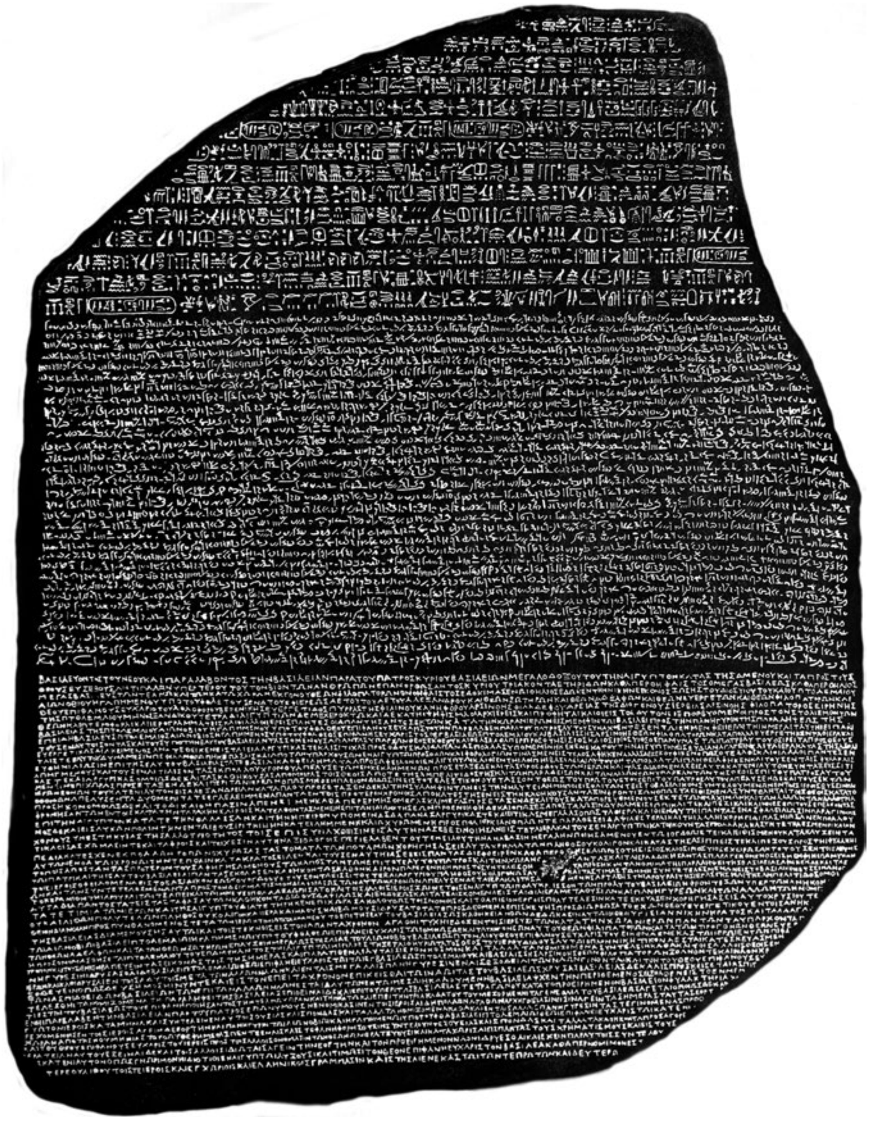

Figure 2.14 The Rosetta Stone, showing three scripts of hieroglyphics (top), demotic (middle), and Greek (bottom). © Peter Horree/Alamy.

We can see, therefore, that this "document," one of the most important historical objects ever found, forces us to confront a very difficult question: who should own it? Egypt first asked for its return in 2003, when Zahi Hawass, Secretary General of the Egyptian Council of Antiquities, stated, "If the British want to . . . restore their reputation, they should volunteer to return the Rosetta Stone because it is the icon of our Egyptian identity." What is the best response to this? Obviously whatever reply is made sets a precedent for antiquities from other ancient cultures. Here, then, are some possible replies:

Answer 1: The Rosetta Stone should stay in the British Museum, where it has been for 200 years. It is safe and well-protected, in contrast to the Egypt Museum in Cairo, which was looted during the civil unrest of 2009–2011. Britain acquired the stone according to international law of the time – the treaty of 1802 by which the French surrendered their collected relics was also signed by the Ottoman and Mameluke commanders, legal representatives of Egypt. The British Museum has made the stone available for study to scholars worldwide and has used the latest technology to analyze it for the betterment of scientific understanding.

Answer 2: The stone should remain in the British Museum. Mr. Hawass's statement is not fully legitimate. Modern Egypt is a legacy of Islamic culture, not the pharaonic civilization. It is not credible that this stone, separated from its global fame, was ever an "icon of Egyptian identity." Islam showed little interest in ancient Nile culture (and even destroyed some of its relics).

Answer 3: The Rosetta Stone belongs to Egypt. Napoleon did not ask permission to enter the country but instead invaded it. His army and scientists had instructions to take back to France anything found of value. This was simply looting by a colonial power, which utterly disregarded any rules of sovereignty. The stone would mean a great deal to the Egyptian people. Britain, meanwhile, is reaping the reward in tourist dollars that should be going to Egypt to help it further improve its museums.

Answer 4: Egypt is where the Rosetta Stone was created and where it belongs. It was carved for inhabitants of the Nile Valley. No matter that modern Egypt is a Muslim country; when the stone was erected, there were Greeks, Nubians, Persians, and Libyans living along the Nile, none of whom shared the ancient culture. Also, returning the stone would be a powerful gesture of international diplomacy, helping mend the image of Britain (and the West) in the Islamic world. Moreover, if Cairo has had problems of violence in recent years, so did London during World War II, when it was bombed by the Nazis.

These replies are reflective of the responses that officials and scholars have given to Egypt's request for repatriation. They do not exhaust what might be said, far from it. But they are enough to show the problem cannot be dealt with in any simple way. The matter is inherently moral, political, legal, economic, and scientific, all at once. Possession of famous artifacts is a matter of deep national pride for some governments and societies.

The British Museum, for its part, seems to have no intention of repatriating the Rosetta Stone. It sees itself, to a degree, as setting a precedent for museums elsewhere around the world. It understands its possession of the stone as fundamentally different from the intentional wartime looting done, for example, by the

Nazis in World War II, who ransacked museums, private collections, and individual homes. Most of what the Nazis took has been returned. Whether we consider this relevant or not, one thing stands clear: the history of the Rosetta Stone is far from over.

The Great Library at Alexandria

But while we debate what should be done with precious historical treasures, we must mourn the loss of another. This is the Great Library that once existed at Alexandria, the port city on Egypt's Mediterranean coast. Yet few may know of the ambitions behind it and how these rendered the town a nexus of intellectual life and scientific discovery.

Alexander the Great conquered Egypt in 331 B.C. and decided to build a great city and intellectual center in Alexandria on the Mediterranean coast. As he did elsewhere, Alexander left one of his military leaders to establish rule over the country and carry out his wishes. Legend has it that a disciple of Aristotle, Demetrius of Phalerum, convinced this first Greek king of Egypt, Ptolemy Soter, to build a great library that would draw scholars from all over the known world, making the new city a rival of Athens. Presumably, Demetrius promised he would deliver to the library all of Aristotle's writings, including his many books on the nature of the world, animals, astronomy, meteorology, and more. This did not happen, yet Ptolemy I carried forward the project, hiring scholars and translators to begin the task of building the library. The primary task, at the beginning, was to translate into Greek the *Old Testament* of the Jews and to write down in Greek all of the knowledge written on the walls of the ancient tombs and monuments along the Nile in order to preserve it. Such, however, was only a "small" beginning. The next stage of work would involve collecting all papyrus scrolls in Egypt on intellectual subjects and then gathering all important works from Babylon, Persia, India, and even China.

The Great Library, as it came to be known, was not simply a storehouse of texts and knowledge. It also became an intellectual and teaching center in its own right, surpassing nearly every other such place in the classical world. Possibly as many as 100 scholars lived, taught, and did research there. It was certainly the birthplace of geometry. Euclid composed his work, *Elements*, that became the basis of geometry in Europe, Byzantium, and Islam, in Alexandria. The openness of the society to intellectual work allowed Herophilus (335–280 B.C.) to perform careful and detailed dissections of human cadavers for the first time. Together with Erasistratus, who came from Syria where he was royal physician, the two men founded the medical school of Alexandria. Their work established, once and for all, that the brain was the center of mental activity, not the heart as Aristotle and the early Egyptians had thought. Aristarchus of Samos did his research into the mathematics and astronomy of the solar system in Alexandria at the library, earning a crucial place in the history of science for the first model that placed the sun at the center and the first six planets (those visible with the naked eye) in their right order. Apollonius of Perga (ca. 262–190 B.C.) produced the hugely influential book *Conics* while working at the library. His study of conic sections (shapes created by planes intercepting a cone), besides introducing such terms as parabola, hyperbola, and ellipse, created the hypothesis of eccentric orbits and epicyclic motion, which the great polymath Claudius Ptolemy (2nd c. C.E.) adopted in his great work the *Almagest*, which itself was written in Alexandria. To name only one other famous scientist who worked at the Great Library, Eratosthenes of Cyrene (ca. 276–195 B.C.) is widely known today for his highly accurate measurement of the Earth's circumference. Yet he did much else, such as estimating the tilt of the Earth's axis, inventing the basic system of latitude and longitude, and conceiving an algorithm for finding prime numbers ("Eratosthenes Sieve"). It appears he came to Alexandria from Athens, in order to serve as personal tutor to Ptolemy III's son and to be the head of the Great Library.

Within a century of Alexander's death (323 B.C.), therefore, his dream of an intellectual center on Egypt's coast had been more than achieved. By the first century B.C., it had eclipsed even Athens – scholars now knew that the two places to gain the highest learning were the school of Posidonius on Rhodes and Alexandria. Galen himself, whose impact on medicine in Islam and Europe was to be unparalleled for more than a thousand years, came to Alexander's city to study. What drew such thinkers was the greatest collection of knowledge the world would ever know. To learn the depths of any field – not least, the sciences – it was essential to come here, where the concentrated deposits of millennia of thought and discovery lay. Estimates on the total number of scrolls range from several hundred thousand to over a million. No one knows the precise number. They do understand the magnitude of loss. Even for a civilization like Egypt's that left such an abundance of relics, we have what amounts to a few isolated fossils from what was once a vast ocean of gathered thought.

There is no final agreement among today's scholars about how the great library was destroyed. Several ancient sources, such as Plutarch's "Life of Caesar" (1st c. C.E.), claim the Roman general accidently caused the burning of the main building when he set fire to ships in the harbor in 48 B.C. during his conflict with Pompey. There was at least one other library, at the Temple of Serapis, which apparently survived with many thousands of scrolls. As a result, Alexandria remained a key center of knowledge and learning for centuries afterward. A second tale, also venerable but not confirmed by actual evidence, has it that several centuries later the Christian Patriarch of Alexandria, Theophilus, had the Temple of Serapis converted to a church, destroying many documents in the process. Even this did not end Alexandria's fame, however, nor its place in the Roman Empire.

Ultimately, the final loss was mirrored by the murder of one of the last great intellectual leaders in the city. Hypatia was the daughter of Theon of Alexandria, a teacher of mathematics and a commentator on Euclid and Ptolemy. Raised to be an exceptional thinker and curator of the remaining library, she excelled as a teacher, mathematician, astronomer, and neoplatonic philosopher. It is likely that she wrote on all these topics and also made several inventions of considerable value, such as the plane astrolabe (a hand-held device for predicting positions of the sun, planets, and stars). Yet in the new Christian era, the great library, or what was left of it, came to be seen as a core of pagan knowledge. Hypatia herself, a formidable mind and representative of Neoplatonism, proved a major obstacle to the new patriarch, Cyril, who intended to rule a fully Christian city. The common story is that in 412 C.E., after expelling the Jews, Cyril incited a mob of monks to attack, murder, and dismember Hypatia, then burn portions of her remains. Religious intolerance was invoked one last time in 640, when Islamic armies entered the city and their general, finding the great gathering of books, had to decide what to do. After listening sympathetically to the Alexandrians, who pleaded that it be spared, the general wrote to the Caliph Omar for a final decision. His reply: "If the books contain knowledge that is opposed to the Qu'ran, they are evil and must be burned. If they contain things that agree with the Qu'ran, burn them anyway – they are superfluous." One tale holds that the manuscripts kept the public baths heated for nearly six months. Such marked the end of Egypt's history as a land of scientific leadership in the ancient world.

It is an ancient desire, surely, to gather and possess all the knowledge in the world. Today we find it in efforts to digitize every book ever printed. A few centuries back, it appeared in the famous *Encyclopédie* of the French Enlightenment and before that in a variety of writings like those of Bartholomeus Anglicus (13th c.), the *Four Great Books of Song* (11th c.), ibn Zakariya Razi (10th c.), and Isidore of Seville (7th c.). Many of these writings we thankfully possess today. What we do not have, the Great Library, came far closer than any other effort to achieving the ultimate goal – not least in the domain of science. Yet this fact too is vital. It tells us that the ambition is worthy and realistic, that the result will provide a magnificent source of inspiration and work but also that any such gathering in one location will be fragile. Such are all key messages for the contemporary practice of science, as it adapts to the new technologies of digital communication.

Concluding remarks

All that we have said gives only an idea of scientific and technological practice in ancient Egypt. Even so, we can see the very high level of rational thought that existed. In Egyptian scientific culture there was a considerable degree of professional organization, one that matched the systematic aspects of the relevant knowledge itself. The Egyptians were driven by their observations, curiosity, and experience, as well as their religious beliefs, to find order in the natural world and to put this to use. Such was entirely necessary for them to build and sustain a society of high refinement for thousands of years.

As hinted at repeatedly, this was also a society that proved intellectually conservative. Scientific knowledge seems to have progressed greatly in the earlier phases of social development, after which its advances slowed, depended on new material from foreign sources, or ceased to advance altogether, preferring instead to rely on oral formula resembling spells. The reasons for this are not well known. They are in all likelihood complex, related to the changing place of knowledge in society and concepts about the value of past achievements. Given what we now know about this society, it would help little to blame such conservatism on a blanket category like "religion." Similarly, saying that the lack of continued advance in science was due to the "rise of magic" seems unhelpful. "Magic" may not be the right term. Egypt's character as a society between the written and the oral, in which medicine (for example) spread ever more widely among the illiterate population, may well deserve more investigation in this regard.

Over the past two centuries, ever since Napoleon came to Egypt in the 1790s, many who have taken the time to learn about Egyptian science and society have expressed their astonishment, just as Herodotus did in the 5th century B.C. For many, this degree of surprise has only deepened in view of the impact Egyptian thought had on Greece and Rome. Yet such amazement has perhaps reflected an expectation that early science was bound to be more primitive and rudimentary than it actually was. In most of the modern period, we have been taught a kind of fable about this. This chapter teaches us that "the scientific attitude," as a way to approach nature empirically in search of insights and principles, is hardly a recent concept. In this, as in so many things, this ancient land provides a lens through which we might view our own time and understand it better.

Notes

1 No single culture is given credit for inventing beer. Egyptians probably discovered how to make it independently, as did other grain-growing societies. Because of yeasts in the air, any wetted grain containing sugars will undergo fermentation naturally. Early beer of this type was cloudy with grain residue, often sweet, and quite nutritious.

2 South face is 756.08 ft. Subtracting the shortest, north face 755.43 ft gives 0.65 ft. Thus, 0.65 ft × 12 inches/ft = 7.8 inches.

3 Stories that mummies were used as fuel for locomotives, as humorously recounted by Mark Twain in *Innocents Abroad*, are not true, though widely repeated.

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3 Land between two rivers

Science in ancient Mesopotamia

> Gilgamesh spoke to Urshanabi the ferryman, "Climb up on to the wall of Uruk, inspect its foundation terrace, and examine well the brickwork . . . did not the seven wise men lay these foundations? One third of the whole is city, one third is garden, and one third is field . . ."
>
> The Epic of Gilgamesh (ca. 1750 B.C.)

One of the world's oldest heroic tales, the *Epic of Gilgamesh*, still speaks to the present. Consider the vision of a sustainable city in the passage above. It is a city planned in mathematical terms, divided into thirds, yet dominated by nature. One third is the metropolis itself, another, embedded within the first, is a carefully designed series of parks and urban green zones (with flowing water and fountains we presume). A final third is devoted to growing, a mixture of organic gardens within the city wall and outside fields for staple crops. It is a vision, then, not of humans dominating nature but using knowledge of it for their needs.

The city Gilgamesh speaks of is Uruk, in ancient Sumer (southern Iraq, Figure 3.1). It is also where scholars and archeologists believe that writing was first invented, about 3300 B.C. The written word has been often called the single greatest intellectual achievement by human beings. Yet it was a technological invention, too, and seems to have needed the city to appear first. Uruk was likely among the very first cities, founded about 3,500–3300 B.C., near the banks of the Euphrates River (Figure 3.1). It occupied roughly 0.75 km^2 of ground and had several thousand inhabitants. The cities of Sumer quickly grew under their individual rulers, developing bureaucracies and social classes, including slaves. As they grew, each came to have its own patron deity, whose authority rested in the king and the priestly class, and whose presence was embodied in a great temple, called a ziggurat, that formed the massive architectural core of each urban setting. Peace was not the way of these earliest city-states. By 2800 B.C., they had begun attacking each other, forming empires, creating a pattern that was to persist for thousands of years in Mesopotamia and that likely spread to Asia and beyond.

The first city-states were built without models. There were no preexisting ideas of what a city or a state should be. The very first of them – Uruk, Ur, Girsu, Nippur, Eridu – were experiments, the first earthly attempts to organize and sustain human life on a mass scale in a restricted space. They were built not of stone or

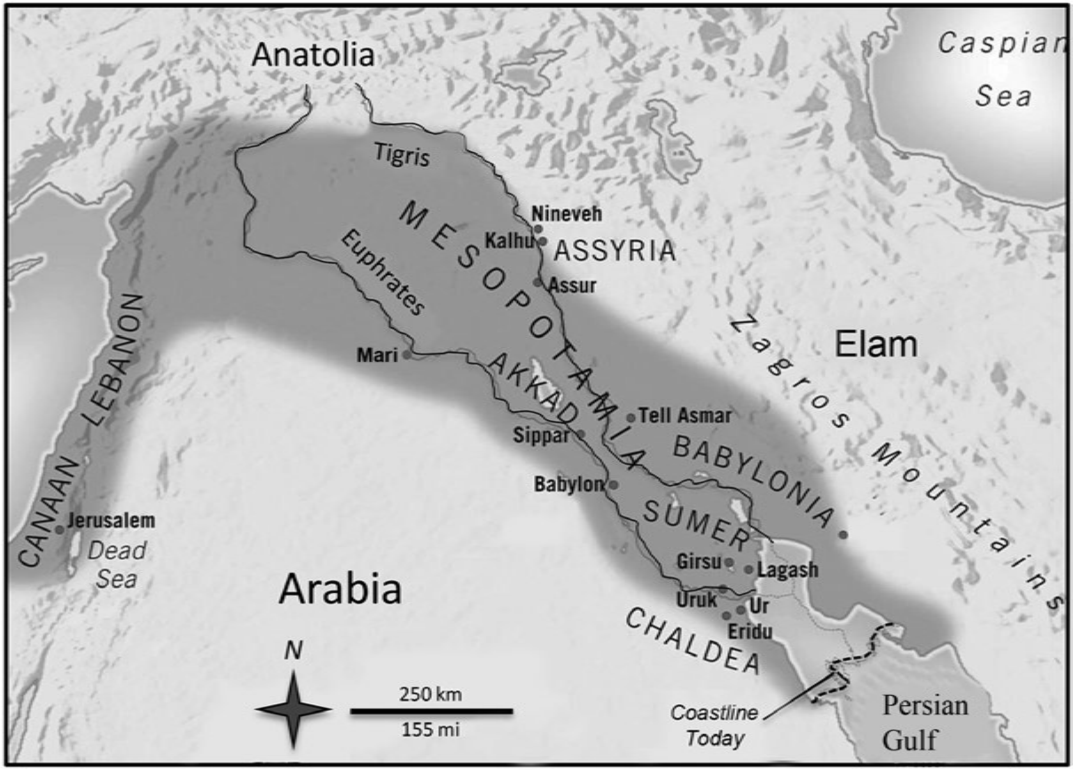

Figure 3.1 Map of the Fertile Crescent region, showing the location of major civilizations (Sumer, Babylon, Akkad, Assyria) in ancient Mesopotamia. Also shown is the shoreline of the Persian Gulf at the time of earliest city-states.

wood but of mud brick and clay-based stucco, materials associated with the immediate river plain and delta-estuarine settings. Based on number of houses, palaces, and so on, archeologists estimate that by about 2,900 B.C. these city-states could have had between 10,000 and 50,000 people and covered nearly 4 km^2. To feed this many people, as much as 2,000–4,000 hectares of farmland were needed, with a system of canals supplying water. Inside the city, people pursued a diversity of occupations with much specialization of labor. Each society was a hierarchy: a king or royal family at the top, with a priestly class just below; wealthy merchants; then soldiers, scribes, artisans, physicians; below them the farmers and laborers; and at the bottom slaves, mainly captives from battles.

Background

Mesopotamia is originally a Greek word meaning "land between the rivers." It is indeed a region gifted with wide open alluvial plains of agricultural richness, a unique area where two major rivers run parallel for more than 700 km. But people first chose to settle in areas along the "hilly flanks," as archeologists call them, at the margins of the alluvial basin and lower slopes of the Taurus and Zagros mountains. These were fairly gentle upland areas well supplied with water, lush with game (goats, sheep, and pigs) and native grains. Settlement eventually spread south from these flank areas in Anatolia (south-central Turkey) at an early date, before 7000 B.C.

Settlements that became Sumer developed after 5000 B.C. along the lower course of the rivers, where the native ecology was rich and where animals and grains from the flank regions were easily domesticated. In the 4th millennium B.C., first the Ubaids and then the Sumerians built systems of canals that ran across the alluvial plain between the Tigris and Euphrates, bringing water to fields, even creating oases. Yet abundance didn't come without a price.

Lack of natural barriers meant frequent invasion, with successive waves of people taking control of settlements. Archeologists estimate that by 3000 B.C., as much as 85–90% of the population of Sumer lived within its high-walled city-states. "Climb up on to the wall of Uruk," says Gilgamesh, "inspect its foundation terrace, and examine well the brickwork." Such walls were a source of technological pride, even boasting, but also survival. Built of mud-brick, however, they needed constant maintenance. Inasmuch as they were something to brag about, they were the products of much organized labor.

Climate and landscape had further impacts. With mild and sporadically rainy winters separated by long, hot, and dry summers, Mesopotamia could never have supported cities without large-scale irrigation. But the two rivers, particularly the Euphrates, the greater source of water for irrigation, were not like the Nile. Their flooding could be sudden, intermittent, and poorly timed with relation to agriculture. Fed by spring snow melt in the mountains of central Turkey, their flooding reached a maximum from late March to May (not in the fall, like the Nile), just before harvest time, when rising waters could do the most damage to mature crops standing in the fields. Flood levels were more variable than in Egypt and could rise unpredictably.

The two rivers also brought problems of salinity. High concentrations of dissolved mineral salts in their water meant that use of this water for irrigating fields could be brutal for fertility. Anytime such waters were allowed to spread and evaporate, especially in the furnace of summer heat, the salts would crystallize out into the top layer of soil, forming a toxic presence. But even more, alluvial soils, a mixture of silt and clay, have low permeability, making it difficult for water to drain laterally away, instead collecting and evaporating under hot sun. Over time, soil salinity can become toxic to plant life, thus agriculture. This seems to have happened in some areas of Sumer.

But there were strong positives too. From southern Turkey to the Tigris-Euphrates delta and north to the foothills and high mountains of the Zagros ranges in Iran, the total region of Mesopotamia included a great variety in landscape and biodiversity. Towns that grew into cities were located in the lower part of the alluvial plain, close to the delta of the two rivers, which then existed more than 100 km upstream from its present location. In this area, there were also estuaries, swamps and marshes. Flooding, moreover, had three important geologic effects: 1) it built broad levees of coarser, sandy material; 2) it left behind dense muds and clay in low-lying areas; and 3) it built up the bed of the river itself.[1] How was all this helpful? Well-drained soils of the levees allowed for cultivation of date palms and fruit trees, as well as vineyards and many vegetables. Clays, cut into mud bricks and then dried, provided building material in an area where stone was rarely exposed. Water levels in the river stayed high enough for irrigation canals to be dug directly to the main channel. Geology was thus more kind than cruel.

Most of all, Mesopotamia had an unparalleled richness of easily domesticated plants and animals. All eight of the so-called "founder crops" were in the immediate region, particularly southern Anatolia where they were cultivated at an early stage, and had come to be traditional foods by the time of the first Sumerian cities (Figure 3.2). These were: einkorn wheat, emmer wheat, barley, lentil, peas, chickpeas, vetch, and flax. Goats were brought down from the Zagros, sheep and pigs from the hills and valleys of southern Anatolia, and cattle from the grasslands of the upper (northern) alluvial plain. Advantage from such diversity was huge; such abundance of food helped counter the grim effects of warfare, which came so often, even as it encouraged invaders themselves. And from such richness the greater realms of Asia, Africa, the Mediterranean, and eventually Europe all eventually drew.

No discussion of this region can pass without reference to the Bible. For example, there is the matter of floods. Early excavations at the city of Ur revealed a thick layer of clay (> 3 m) above normal alluvial sands. This speaks of a massive and long-lived flood, a drowning of lowland areas that lasted years and probably covered the entire lower alluvial plain, bringing enormous destruction. This layer, which dates from the mid-4th millennium B.C., separates older, Ubaid remains from Sumerian relics. The event it marks has been speculatively associated with the biblical flood of Noah.

On the other hand, the Book of Genesis 2:10–14 speaks of the river that flows out of Eden dividing into four, and "the fourth river is Euphrates." Scholars have

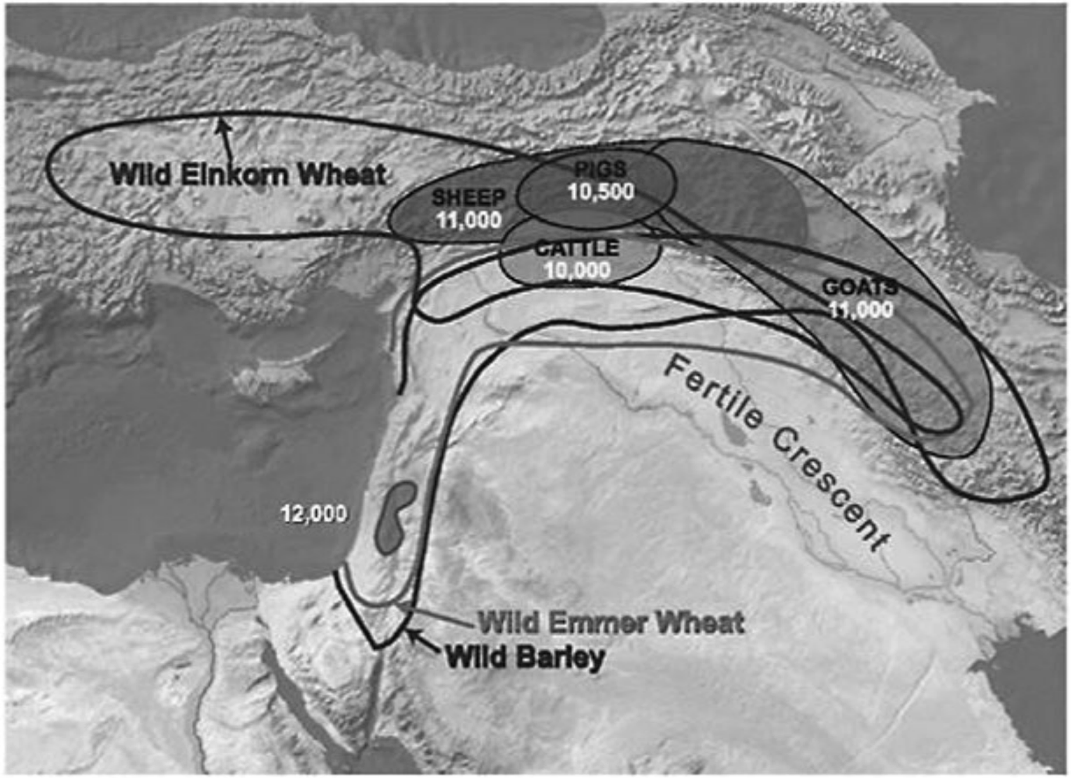

Figure 3.2 Map of the Near East showing areas of early domestication of pig, cattle, sheep, and goats, as well as cultivation of three "founder crops": emmer wheat, barley, and einkorn wheat. Years refer to before the present.

identified the lush, lower marshlands between the Euphrates and the Tigris to be one of the likely models for the Garden of Eden. This area is now covered by silt, mud, and sand; the marshlands have migrated tens of kilometers to the southeast, as the rivers have built seaward. Up to the 2nd millennium B.C., they were much nearer the coast and contained shallow, freshwater lakes. It was in this downstream area that the cities of Sumer were built. The marshes remained an environment of blossoming vegetation and wildlife, including many species of birds, fish, reptiles, and mammals, comprising an oasis-like domain in the surrounding desert. It is not hard to imagine how this could have seemed like a paradise.

Genesis 11, meanwhile, tells of a great tower an arrogant humanity tried to build to heaven and which God halted by breaking speech into a thousand tongues, ending all cooperative work. In this case, one or another of the great ziggurats, possibly that of Babylon (18th century B.C.), was a possible source. The most detailed description of the Tower of Babel occurs in the *Book of Jubilees*, a Hebrew work also known as the "lesser Genesis." Jubilees 10:20–21 says the tower was indeed built in Mesopotamia and that "they began to build, and in the fourth week they made brick with fire, and the bricks served them for stone, and the clay with which they cemented them together was asphalt which comes out of the sea, and out of the fountains of water in the land of Shinar."

Asphalt, or, more accurately, bitumen, was yet another natural resource of the land between two rivers. *The Epic of Gilgamesh* mentions it a number of times, e.g.: "The gate of grief must be bolted shut, sealed with pitch and bitumen!" Surface oil seeps were well known, probably even mapped in some fashion, from very ancient times. They existed in sizeable number along the middle portion of the Euphrates, near present-day Ramadi, which would have placed them near Sumer in the 3rd millennium. They also exist on the sea floor of the Persian Gulf, and a significant amount of this material was washed up on various shores, ready for collection and use. Records and relics both prove that the Sumerians, Babylonians, Assyrians, and later Mesopotamians used bitumen to mortar their buildings, seal and waterproof ships, light their torches. Even more impressive, from the modern standpoint, it was sometimes employed to pave roads.

Finally, we should speak briefly about political history. A simplified chronology would begin with the Uruk Period (4000–2900 B.C.) and the realm of Sumer, which ruled mainly the lower, more fertile part of the region. The Sumerians, who referred to themselves as the "black headed ones," a darker skinned, Semitic people, probably from the east (Iran? India?), replaced the Ubaid culture, which had itself replaced the Eridu and Halaf peoples sometime in the 6th millennium B.C. Sumerians proved to be more inventive, industrious, and long lasting than any of their predecessors. By about 3100 B.C., they had built a set of roughly a half-dozen flourishing urban communities, which soon grew to nearly two dozen. As these cities grew in size and number, they began to compete with each other, possibly over land, trade that brought in essential materials (metals, wood), or simply desire for power. By 2700 B.C. an era of conflict set in, with city-states conquering their neighbors, establishing empires, then being conquered in turn.

From this point, empire-building became the pattern of state growth in the Near East. This pattern was taken to the next level by Sargon the Great, who, in roughly 2330 B.C., rose to the throne of Akkad to take command over all Sumer and then to extend his dominion into Syria, Anatolia, and Elam (western Iran). Yet the Akkadian Empire lasted a mere 150 years (a major drought may have weakened Akkadian power) before another period of invasions and warring states ensued. This was ended by King Hammurabi of Babylon, who, in 1750 B.C., reestablished centralized control and stability – as reflected in the famous Code of Hammurabi, the earliest known written system of law and justice for a large political entity. Babylonian sovereignty ushered in a new epoch of intellectual efflorescence, but did not last. Invasion in northern Mesopotamia weakened Babylonian control, which was then destroyed by the Hittites, who sacked Babylon itself. About 1350 B.C. the Assyrians took over the region and were followed in 600 B.C. by the Chaldeans, who were themselves conquered by Alexander the Great in 332 B.C.

The formation of empires, though destructive, also created larger and larger areas over which the same laws, language, and knowledge were spread and from which intellectual materials were drawn to productive centers. Roads and waterways were built to better unite parts of the kingdom (and to collect taxes). Trade and negotiation with surrounding states was required to determine and protect borders, leading to further influx of ideas from farther afield. Unlike Egypt, Mesopotamia both suffered the destabilizing effects of many peoples in conflict, yet benefited during times when the intellectual contributions of these peoples could be combined.

City and stylus

What link was there between the birth of the city and the invention of writing? What explanations can we find here? What, in fact, was this writing about? Let us start with the last question. It wasn't scientific or medical writing. Nor was it religious or political, whether hymns to the patron god or lists of kings and princes. There is nothing in the least imaginative about it, nothing literary or poetic, like the *Epic of Gilgamesh*.

It was mainly bills and accounts. That is, accounting records about land bought and sold, quantities of food, animals, slaves exchanged or purchased. Moreover, these writings weren't carefully preserved. They were thrown away, like daily receipts. The reason we have them at all, and so many of them, is that they were used as filler in building walls, along with broken pottery, smashed mud bricks, and other dross. In today's terms, they were urban waste. We are forced to realize that writing was invented not to express the depths of human feeling or to record knowledge of the world but to do accounts and keep records.

But now consider: what did this really signify? First, that the daily workings of key domains like agriculture, trade, and the economy as a whole, had come to exceed the ability of human memory. Transactions had to be documented, because people's activities had grown to be very diverse, specialized, and because there was a need for ways to keep order. It also meant that society had become stratified in a complex way, with landowners and merchants, peasants and slaves, craftsmen and bureaucrats, as well as a specialized class of scribes who knew how to employ symbols that could translate everyday events into tangible, shared language. The keeping of accounts meant that the economic actions of civilization could be regulated and recorded – which, in turn, meant that they could be, in some part, controlled, planned, traced, and expanded. And there is another crucial thing to note. To keep accounts and record transactions required a numbering system, complete enough so that advanced arithmetic could be done. The earliest writing system therefore brought *mathematics* and the powers of planning, organization, and control that this allowed. It meant, too, that literacy could not have been restricted to a single class of scribes. It had a diversity of users.

There is more to ponder. Early Mesopotamia, during the key period of 3500–3000 B.C., was the site of yet other momentous technological inventions. The plow, drawn by domesticated cattle, appears to have had its first use in this region. Such may also be true of the sail (though Egypt seems to have had this invention around the same time). The wheel appears in diagrams on clay tablets found at Ur, dating from 3500 B.C. Since these images show something already in wide use, the true invention was significantly older. Archeologists believe it could have happened in several other regions independently, particularly Asia, East Europe, and the Caucasus.

These were inventions that came to change the world. Of this, we can have no doubt. But they didn't do so immediately or directly. The wheel was invented to make pots. Pots were far more important, early on, than carts or wagons. Pots were everywhere in society, used by poor and rich alike. Pottery gave humans the ability to boil and steam food, thus bringing many new sources of nourishment (e.g. shellfish, leafy vegetables, roots), as well as store grain and mix medicines. Pots were key to urban settlement. Pottery wheels allowed mass production of this critical good. Transport was not long behind, to be sure. Chariots appear in Sumer by about 3200 B.C., roughly coinciding with the building of great walls around Uruk and nearby metropolises. But it was the science of clay and the technology of the wheel that helped make the city possible.

Farming and irrigation

What is a city? There are many definitions. Numbers of people (per square area), total size, level of commerce, social and bureaucratic complexity – all of these have been used to define urban centers. Yet we can look at the subject a bit differently. A city can also be understood, especially in its earlier phase, as a place where population, knowledge, and technology all come together to provide large-scale sustenance and resources necessary to a permanent settlement.

By any measure, food was key to any early-stage city. Having a large, reliable supply of it could free much of the population to engage in other work, whether this be religious in nature, bureaucratic, military, craft-related (metalwork, stonework, sculpture, arts), scribal, or medical. We saw in Egypt that to be successful on a large scale, agriculture had to be based on scientific knowledge as well as technological invention. In Mesopotamia, the understanding of how to cultivate founder crops, using simple irrigation, and to raise what we might call "founder livestock" was acquired before 4000 B.C. Unlike Egypt, flocks of domesticated sheep and goats were kept by nomadic peoples in northern Mesopotamia as early as 7000 B.C., with cattle and pigs following soon after. Knowledge of how to raise and use these animals was far-reaching – what grasses to feed them; how to aid the birthing process; cross-breeding to improve certain characteristics (e.g. milk production); how to care for sick animals; use of dung for fertilizer; how to use leather and wool for clothing, horn and bone for tools and weapons, fat for tallow (candles). This knowledge was extremely important. But it was not enough to urge the creation of cities.

For this, something more was needed. Farming had to move from small plots, worked by individuals, to a more commercial-level enterprise, with larger fields and more efficient techniques. Two forms of technology were essential: the ox-pulled plow and an extensive, well-organized system of irrigation. Before 3300 B.C., the plow in Sumer was a sharp implement of stone, horn, or wood fastened to a fork-like stick, which was held firm and guided by the farmer as it broke up the soft, alluvial soil to a depth of about 15 cm (6 inches) in long rows. Seeds would then be tossed into these rows and covered. But then came the Bronze Age (~3300–1800 B.C.) and a profound innovation. The first seed plow consisted of a bronze wedge to break the ground more fully and a long-stemmed funnel sticking up vertically just behind it. As oxen dragged the plow forward, gouging out a furrow in the soil, a second man dropped seeds down the funnel and into the furrow where they would be covered over by the soil falling back in. Simple though it sounds, the invention was momentous. Not only did it allow for much less labor to plant large areas and for fewer seeds; planting could take place far more rapidly and with improved results – more seeds ended up in optimal positions for germination than when they were scattered by hand. Harvests, therefore, increased considerably on the same land.

Irrigation in Mesopotamia was ancient even by the time the Sumerians took control. Ubaids had drained part of the marshes and dug canals. But under the hand of Sumer, irrigation became a massive, state-sponsored system, organized and planned and then maintained by a large labor force. It was far more extensive, as a system, than in Egypt, and it took water many kilometers across the alluvial plain. Especially long and wide canals provided sites for a string of settlements, some of which later developed into cities of their own. Early hydro-engineers (let us call them this) created simple networks of canals fed by channels from the two rivers. These provided good water in the dry season for the small fields tended by villages. But as populations grew and towns replaced smaller settlements, the network of canals was greatly extended and systematized. Fields became long and narrow, to maximize the efficiency of irrigation by the surrounding canals. To prepare these fields for sowing, a fairly complex process was used. This took place in the fall, either after the first rains had soaked the ground or, if these were late, after gates to the river were opened and water allowed to rise to where it flooded the fields (most fields were below the level of the river).

According to "The Farmer's Instructions," an early text from the 2nd–3rd millennium B.C., the topmost soil needed to be first wetted, then weeded, hoed, and even, if needed, pounded to a level surface. Next, the ground had to be broken up by shallow plowing and then raked, with large clods "pulverized fine with a hammer." Finally, "When you have to work the field with the seeder-plough," says the text, "keep your eye on the man who puts in the barley seed; let him drop the grain uniformly two fingers deep. Use up one shekel of barley for each garush" (*shekel* was a weight of about 180 grains, *garush* an area of roughly 22 m^2 or 27 square yards). It is advised that furrows be spaced roughly 0.75 m (30 inches) apart and the field be watered three or four times before harvest at specific intervals (e.g. when the sprouts have filled the bottom of the furrow; when they have reached the height of "a [straw] mat in the middle of a boat"). After the harvest, sheep and goats are to graze on the remaining stubble and to fertilize the soil with dung.

Flood control, however, remained a challenge. Early dikes built by digging and dredging tended to dry and erode in the wind and so were sometimes breached. Moreover, because of aggradation (see footnote 1), the bed of both rivers was often above the level of the surrounding plain, which meant considerable destruction when such breaching occurred. A second challenge came from the high levels of suspended silt and clay (higher than the Nile), able to choke irrigation canals. Worst of all was the high salinity, especially of the Euphrates, which caused progressive loss of soil fertility, thus reduced productivity in areas where water spread over the fields and then evaporated, instead of being drained away.

The first of these problems was handled by a system of diversion dams, meant to slow and redirect flood waters, for example into reservoirs encased in dikes and into gated canals. Stronger dikes, at times made of mud bricks, continually inspected and maintained, were also built. Early engineers also saw that the Euphrates is topographically higher than the Tigris, and so they could drain irrigation and sometimes flood waters from one river to the other (obviously, this did not work all the time when both rivers were in flood). Silting up of irrigation canals, meanwhile, could only be handled by dredging. This meant periods when many men would have to work the canals to scoop out the silty muds. These were piled onto or around the dikes. As for salinization, this remained a problem without a solution. By the time of Herodotus (5th c. B.C.), rising soil salinity had made some lands utterly barren and others barely capable of agriculture. Scholars debate whether widespread salinization in the southernmost areas caused a shift northward in the center of Mesopotamian civilization by the later 3rd millennium to Akkad and then Babylon. Such a migration certainly did happen, though the causes remain unclear. Changes in crop selection may or may not have been involved. In the area of Sumer, these show a shift between 3000 B.C. to 1900 B.C. from mixed wheat and barley to only barley, which is by far the more salt-tolerant plant.

Food

What did the Sumerians and Babylonians eat? What would we have been served, had we been a craftsman or priest in Uruk or Nineveh? It so happens that we have lists to tell us, written on tablets as old as 2900 B.C. What we do not have are actual remains of food, as in Egypt, or early books of menus. From word lists, we know Sumer had a great variety of edibles at its disposal – cereals, fruits (fresh and dried), vegetables, fish (mainly freshwater), birds, and meat products, including dry ones ("jerky") from domesticated and wild animals. Nearly a hundred names of vegetables are given. Garlic, leeks, and onions were all viewed as excellent for health and were consumed regularly by all levels of society. In one of the more extensive lists, which reads partly like a recipe book, there are long sections devoted to the preparation and use of soups, beers, and breads, with shorter segments on syrups and honey, spices, oils, cooking fats, grains, fruits, melons, and dairy products. While specific names and uses aren't always clear, it seems that many foods, like fruits, dates, melons, and roasted barley, were sold in the streets and in marketplaces throughout a city.

Despite such variety, most of the population, particularly the lower classes, subsisted mainly on barley, roasted and made into bread, plus a few fruits (dates, apples), and some vegetables. Vegetable stews, starchy soups, often well spiced, were also common dishes. There were taverns that sold beer; wine was consumed mainly by the wealthy. We shouldn't assume that the farming class ate well; often they did not. A famous proverb of the time advises: "When a poor man has died, do not try to revive him. When he had bread, he had no salt; when he had salt, he had no bread." This kind of "portrait" tells us the earliest city-states were not kind to the poor who nonetheless did most of the labor on which urban life depended.

The most popular fruits were apples, figs, dates, and pomegranates, with the first two eaten fresh but also dried, an innovation that allowed these nutrient- and sugar-rich foods to be stored and carried on trips or military expeditions. Great favor was given to dates, fresh and dried. Large plantations of date palms existed along irrigation canals and river tributaries. As in Egypt, the flesh and juice of the fruit found many uses: as a sweetener in both cool and hot drinks, a syrup for flavoring other foods, and an ingredient in medicines. Throughout the Near East, a realm of agronomy surrounded the date.

Meat, though abundant, was restricted to the upper classes, as in Egypt. Sheep, cattle, goats, and pigs were all consumed, as were gazelle and fowl. These were also preserved in dried form, through salting and outdoor desiccation. Pork seems to have become taboo after 2400 B.C., probably for religious reasons. Often, the best cuts of meat were offered to the gods, then eaten by priests. Ritual animal slaughter was widespread, so it seems the priestly class and its retainers were well-fed. A good many of the recipes thus far discovered are focused on meat dishes and include stews, meat pies, spiced roasts, and more. Stews of various meats, spices, vegetables, and fats were simmered in covered pots. The Babylonians knew the craft of sausage making, taking spiced meat and stuffing it in animal intestines. Common spices used with meat were garlic, coriander, mint, and cumin. Dairy products, mainly butter and various cheeses, were widely eaten and were especially on display during parties given by the wealthy. Milk, however, wasn't a favored liquid, most likely due to problems of preservation.

Many records show the consumption of fish up until about 3000 B.C., after which it ceases to be regularly mentioned, for unknown reasons.

Keeping it fresh

Preservation of meat by drying and salting was a world-changing invention. Both in its original and extended forms (smoking, brining, etc.), it came to be practiced by every major civilization and is no less crucial today where refrigeration is lacking.

Salting came first. Pliny the Elder, in his grand survey of Roman Science, *Natural History*, said, “Heaven knows, a civilized life is impossible without salt,” a meaningful statement, given that Rome controlled nearly all the salt mines in the Near East. Rome, meanwhile, learned the process from the Greeks, who acquired it from the Babylonians and Egyptians, who in turn inherited it from the Sumerians.

Meat curing – *charcuterie* in modern terms – was first developed on a large scale around 3300 B.C. and seems linked to the first cities. We don’t know if the Sumerians inherited or invented the process, but they certainly advanced it to include not only meat, but fish, fruits and figs, all of which they apparently used for export.

What scientific knowledge was needed? Putrefaction, i.e. bacterial growth by which meat is poisoned, had to be prevented. The Sumerians understood moisture was the key factor. The easiest way to remove it was outdoor drying, but knowledge of *how* meat dehydrates was needed. The first day in a hot, dry climate sees more than half the original water content evaporate, causing shrinkage and major weight loss, but thereafter the process slows considerably. To accelerate it, the Sumerians learned to cut meat into thin strips of uniform size and thickness and to expose them to maximum hours of warm circulating air, producing a reliable “crop” in only a few days. Workers turned the strips over and used fans for air movement and waving away flies. It was found early on that maximizing exposed surface area was best, i.e. hanging strips by hooks or string, instead of laying them over poles. It was also seen that leaner parts of the carcass work best. Animals, therefore, had to be well-chosen: middle-aged, well-exercised beasts were preferred. Pigs were not used, due to their high fat level.

For salting, another domain of knowledge was developed. Mineral salt and its interaction with moisture and fresh meat had to be understood. Pure NaCl produces the most rapid dewatering, but does not kill bacteria, only retards their growth (Na^{+} and Cl^{-} bind to water molecules, preventing their use by bacteria). The best results, including preservation of color, came from salts with small amounts of sodium and potassium nitrate, which do eliminate most putrefying bacteria. The Sumerians found that salt from seasonal saline lakes, which became salt pans during the dry months, worked best.

The Sumerians also figured out that they had to thickly cover the entire piece of meat with salt and press it into the flesh. Many different cuts of meat, not just thin strips, could be preserved this way. For best results, two or three weeks were required for full desiccation. This gives the salt time enough to both dry the meat and to impose biochemical changes in the tissues, creating more interesting and complex flavors.

All of this tells us that food preservation used techniques based on knowledge about mineral salts and their effects on animal tissue. Without such knowledge, gained through observation and experiment, perhaps over many years, no such work would have been possible. Every time a ham or turkey is "salted away," as we say – meaning packed in salt and stored for a time – we are employing understandings of nature that were acquired more than 5,000 years ago and put to work in humanity's first true cities. Such might give us reason to think about the history of science in a new way. In how many other areas of modern life, from the making of bricks to perfume, might this be true?

Mathematics

Mathematics and writing developed about the same time in Sumer and for similar reasons. The need to document economic abundance and exchange was linked to the centrality of trade in Sumerian life, and it proved a means for keeping accounts, creating administrative records, and imposing laws. Prior to the rise of the Sumerians, people in Mesopotamia used tokens to keep track of goods, e.g. a clay chip to denote one goat or a handful of grain. Individual symbols were next invented to stand for representative quantities, like two or ten, to make record keeping much easier. Between roughly 3300 and 2900 B.C., these symbols evolved into a numbering system that allowed for counting and documenting into the millions, as would be needed by a city-state providing for tens of thousands of people. The system, however, was multiple: different signs were used to count different things. Thus, simple arithmetic (addition, subtraction) was possible within each group of objects but nothing more sophisticated could be done.

During the course of the 3rd millennium B.C., a major change took place. The pictographic writing of the early Sumerians was replaced by a new, more abstract and elegant system of wedge-like symbols, known as *cuneiform* ("wedge-shaped") (see Figure 3.3). These were probably difficult to learn, but over time a scribe could inscribe them fairly quickly using a kind of stylus with a triangular end that would be pushed into the wet clay of a tablet at various angles. Along with these symbols there evolved a single numerical scheme (Figure 3.3) that was very easy to learn and could be used for counting, arithmetic operations, and far more advanced calculations of varied type. This scheme used only two basic symbols, a vertical "lamp" for digits 1–9 and a sideways "wing" to denote tens. Both of these are then increased in number and combination to render all higher numbers (Figure 3.3). The oldest known tablets showing this scheme date from around 1900–1600 B.C.,

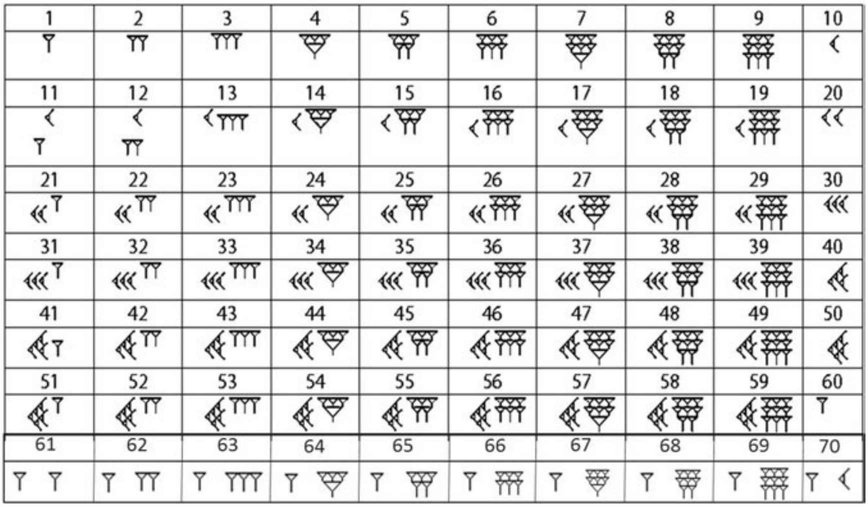

Figure 3.3 Number system used by Babylonians, in base-60. Cuneiform symbols for each number are shown.

thus from Babylonian times. Because it is used in sophisticated fashion on these surfaces, archeologists believe the scheme was invented significantly earlier, probably by the Sumerians.

It is a sexagesimal system that uses place notation. This means, as shown in Figure 3.3, that it is a base-60 scheme, using powers of 60 (we use a base-10 scheme). It has separate symbols or combinations of symbols for 1 through 59 and then begins over again – note that the symbol for 1 and 60 are the same. Like the Egyptian system, the symbol for 1 is simply repeated to produce 2, 3, 4, up to 9 in neat arrangements.

But the Sumerian-Babylonian system had a powerful advantage over the Egyptian version. Use of place notation allowed numbers greater than 59, up to innumerable millions, to be fairly easily written. Such notation works in the following way: a column or place on the far right is reserved for numbers less than 60; the next place to the left begins with 60, and the next place left of that begins with 60^2. Places were written with spaces between them (historians of mathematics insert commas). For example:

The number 2, 1, 1 can be written as $2(60^2) + 1(60) + 1$, which $= 7{,}261$

Another example: $3, 20, 11 = 3(60^2) + 20(60) + 11 = 10{,}800 + 1{,}200 + 11 = 12{,}011$

The system was a huge advance, visually and conceptually. The algorithms for addition and subtraction, including carrying and borrowing, allowed much quicker and easier calculations. A repeating base system and place notation together allowed for the posing and solving of many complex equations. It shows that the Sumerians/Babylonians understood the concepts of exponents (to the second and third power, at least) and, therefore, roots. They could solve linear, quadratic, and even some cubic equations, and they also worked with reciprocal pairs (numbers that multiply to give 60).

To our modern eye, the system seems cumbersome and a bit confusing to use. Moreover, it can sometimes be difficult to tell in which notational place a particular number occurs. Scribes always left a small vacant space between places, i.e. to divide those numbers filling the first place (1–60) from those in the second (61–3,600), and so on. Yet such spaces were created in wet clay, and when clay is fired in a kiln it tends to shrink. The result, no doubt, was almost always clear to scribes, but to modern translators there are more than a few tablets whose meaning remains difficult to discern.

Babylonian scribes understood the geometry of a circle. The basic concept of π, as a constant for calculating circumference and area irrespective of the actual size of a circle, was clearly known to them. But there doesn't seem to have been a need to determine these calculations precisely. Circumference was determined by merely multiplying the diameter times 3 (instead of 3.14159. . .), while area was taken as one-twelfth the square of the circumference, again based on a value of 3 for π. This was done even though more accurate estimates of π (3 1/8) were known.

Precision enters in when squares and triangles are involved. Indeed, one of the most impressive indications is the famous YBC 7289 Tablet (Yale Babylonian Collection #7289), shown in outline and interpreted form in Figure 3.4. At first glance, there is only a simple diagram, a crude square with diagonals, plus three numbers – what could be so remarkable here? First, we note that the side of the square is labeled with the number 30. Second, we see that the other numbers need to be read to the right, i.e. the upper figure as $1 + 24/60 + 51/60^2 + 10/60^3$, which equals 1.41421296, carried out to nine digits. This number might ring a little familiar, perhaps, if we remember our geometry, very familiar. It is very close to the square root of 2, which is 1.41421356. Then, when we multiply 30 by this number (in base 60), we find that, indeed, it equals the third number, 42,25,35 (42.4263888). What we have, in other words, is a rudimentary version of the Pythagorean theorem – as a pocket reference we can carry with us.

As we walk over the newly drained fields, muddy and without markers after the spring floods, we need to lay out boundaries and divisions of barley rows for several farmers (they do not always get along; we need to be precise). Next week, we are assigned to examine a site within the west quarter of the city, newly cleared for a large storeroom. Again, precise delineations are required for the size of the building, plus triangular areas inside where grains of different ages will be stored. For both tasks, we are fully prepared with the help of our pocket guide. Most likely, we will have memorized it after the first several uses or so, after which we can donate it to our bumbling apprentice.

Four thousand years later, what strikes the mathematician about this little mnemonic device is not just its existence but its accuracy. There could have been no possibility of arriving at so good an approximation of the square root of 2 by any

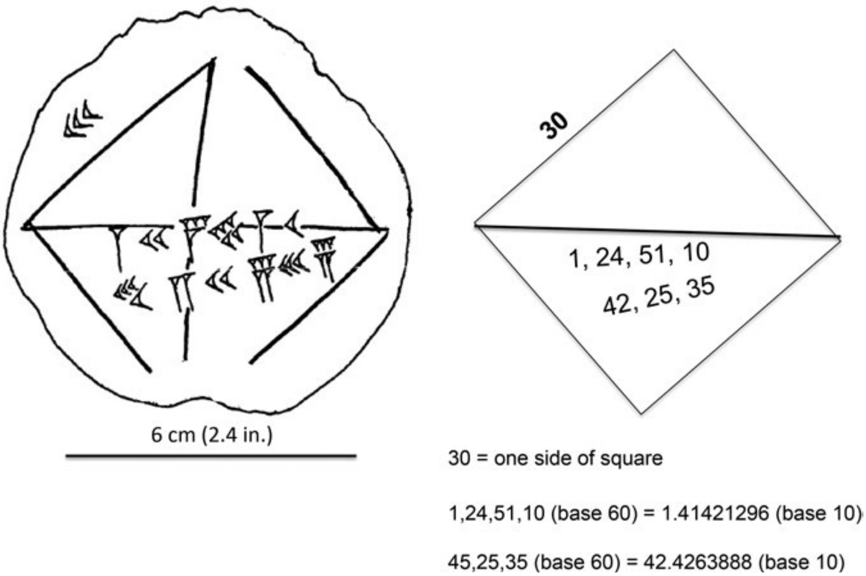

Figure 3.4 Drawing of clay tablet figure (left) showing knowledge of the square root of 2 (1.41421296) and its use to derive the length of the hypotenuse in an isosceles right triangle with the other two sides 30 units in length. See text for discussion.

existing form of measurement. The Babylonians (this tablet dates from the 2nd millennium B.C.) understood that the ratio of the square's diagonal to its side was this number, and they were able to calculate it out to at least nine places. We have to wonder, too, if they realized that it was an irrational number, without any end.

But there's another feature here to dwell on. Looking at the drawing itself, its form, we see that the lines etched by the scribe do not meet very well, even though it's clear they should. One of the diagonals isn't even straight, but looks drawn without a straight edge. Compared to the precision of the numbers, the image seems rather hastily made, for purposes of illustration or teaching but not for any permanent display. Even as a kind of pocket reference, then, YBC 7289 doesn't look very professional.

So we come to a larger point. Much of what remains to us as mathematical artifacts from this era are tables and word problems. Perhaps the most famous table is the so-called Plimpton 322 tablet, which is a table listing many Pythagorean "triples" – that is, all three integers satisfying the equation: $a^2 + b^2 = c^2$. But there are many examples of word problems that would remind us instantly (perhaps painfully) of homework exercises in middle school ("inside a square with a side measuring 60 rods are 12 triangles and 4 smaller squares; what are their areas?").

These artifacts remind us very much of Egyptian relics in this sphere. What seem to have been preserved are materials used for teaching and learning, materials that were especially abundant. Teaching and learning define core activities for urban civilization, certainly one that survived for thousands of years. These artifacts, therefore, are evidence of a highly organized society, well able to perpetuate itself through the applied use of knowledge.

Finally, why did these people choose a sexagesimal system? The word "choose" implies that they sat down, considered alternatives, and, after considering various rationales, put the matter to a vote. Perhaps, then, to avoid this kind of implication, we might say "develop." But then, why did they remain with it, for it lasted well into the Greek and Roman periods? Scholars don't really know. There are many opinions, most of them based on some sensible, mathematical consideration (the large number of factors in 60, for example). Given that mathematics was an eminently practical pursuit, this makes eminent sense. Yet there might well be more to it than that.

The idea of number itself had a relation to order in the universe – something the modern era has always believed, as shown by Galileo's famous claim that mathematics was the language in which God wrote the cosmos. For early civilizations, the power of numbers to give structure and predictability to things, to connect the human dimension with the ultimate powers, was profound. Depending on religious ideas about time and nature, certain numbers were understood to be fundamental to all reality, like the thread of a divine unity or plan running through creation. For the Egyptians, this number seems to have been 12 (the number of joints in the hand's four fingers and in lunar cycles during a year); for the Sumerians and Babylonians, 60. For the Mayans, as we will see in a later chapter, it was 20, for other reasons.

It is our number, too. Or, at least, one of them. We owe to the Egyptians the division of the day into 24 hours. Yet we live, second by second, minute to minute, in sexagesimal time: 60 seconds to a minute, 60 minutes to an hour. Greek mathematicians and astronomers, specifically Eratosthenes and Hipparchus, used the base-60 system of the Babylonians to divide the spherical Earth into 60 parts, using lines of latitude and longitude, which Claudius Ptolemy later accepted and partitioned further. Ptolemy subdivided each degree of latitude/longitude into 60 *partes minutae primae* and each of these further into *partes minutae secundae*. Such became, over time, due to the enormous influence of Ptolemy's *Almagest*, known as "minutes" and "seconds."

It would be wrong to stop here, however. For we live in the grip of the sexagesimal system in another way too. Every circle, we know, has 360°, an arbitrary number (not in nature). Such came from the Sumerians or Babylonians, though we don't know exactly how – possibly, based on their base-60 scheme, they counted the number of days in a solar year as about 360. Such is a common story; yet, it doesn't sound like the Sumerians to be so inexact. Another tale holds that the Babylonians understood that the perimeter of a hexagon equals six times the radius of the circumscribed circle and that this somehow led to the use of 360°. While we may never know the actual reason, we can credit (or blame) these ancient Mesopotamians for donating, through a long process of inheritance, the entire universe of angles and degrees, therefore, innumerable measures and calculations, from ballistics to the compass.

Astronomy

It is often said that Mesopotamia was the birthplace of scientific astronomy. Such statements are distracting, in a way: they seek to answer "who were the first moderns." For historians, and for history itself, the question has little meaning. The real issue is influence: which cultures developed knowledge that was seen by other peoples to be worthy of adoption and expansion. By this metric, Sumerians and Babylonians do indeed earn our highest respect.

What we know of Babylonian astronomy, we mostly owe to the work of three Jesuit fathers: Johann Nepomuk Strassmaier (1846–1920), Joseph Epping (1835–1894) and Franz Xaver Kugler (1862–1929). They labored tirelessly for decades to decipher cuneiform writings, sensing their efforts would reveal information of considerable value. They were entirely correct in this.

Their efforts gave us the oldest surviving text on planetary astronomy. This is the Babylonian Venus tablets of the *Ammisaduqa* (*Amiza-duga*) period, tenth king of Amurru dynasty, from the early 2nd millennium B.C. These tablets document a complete set of observations of Venus rising and setting for more than 21 years, from 1702 to 1681 B.C. For days when visual recordings were not possible, due to clouds or mist, calculations were made on the basis of earlier and later observations to interpolate the exact rise and setting of the planet. The tablets show astronomers were aware that Venus appeared five times in eight years in the same places, as seen from the Earth. This reduces the synodic period of Venus – its orbital period or "year" relative to the Earth and Sun – to 584 days. In the Babylonian tradition, Venus was associated with the goddess of love and fertility, Ishtar. This gives a strong hint of how influential Babylonian astronomy became, given that this same association was adopted both by the Greeks (the goddess Aphrodite) and the Romans (Venus).

Another series of tablets, called *mul-apin*, written about 687 B.C. or after, contain a compendium of a great variety of astronomical observations. This includes extensive lists of stars and constellations, as well as the dates of their heliacal risings (heliacal = just before sunrise). Another list gives those pairs of stars that, in terms of observation from Earth, rise and set at the same time and that lie opposite to one another on opposite sides of the night sky, so that when one rises the other sets. Still other lists give the highest point (culmination) reached in the sky for a variety of stars, as well as those stars and constellations through which the Moon moves during its yearly cycles. Solstices, equinoxes, and appearances of Sirius, brightest star in the night sky, were also provided in the *mul-apin* tablets.

These tablets contain other information that suggests they were used for astrological purposes, as well as a reference for later astronomical observation. As in Egypt, no real division existed between these two domains, astrology and astronomy. Nor could it. Sumerian and Babylonian understanding populated the heavens with gods and goddesses, including the planets, Sun, and Moon. The movements of these bodies traced out the paths followed by the deities in their preparations for creating events on Earth. In the *mul-apin* tablets all of this is in play. There is mention also of which stars are associated with the four main winds. The major stars and constellations, moreover, are divided according to three great paths through the sky, each associated with a principal god. Moreover, a number of astrological omens are discussed. There is also a mathematical scheme given for the rising and setting of the Moon during each month.

Based on these tablets we can safely assume that the Babylonians assigned coordinates for various points in the sky, similar to the latitude and longitude system that we have today. The ecliptic was divided into 12 parts of 30°, and a zodiacal constellation was assigned for each part. Each of the three star paths noted above related to a particular celestial latitude as well. That the *mul-apin* is a compendium, a compilation of different existing parts, tells us that most of this knowledge existed for some time before the date these tablets were inscribed. Based on the star positions given, scholars have determined that a number of observations were made between 1400 and 900 B.C.

In fact, the Mesopotamian tradition in astronomy and astrology developed for nearly 2,000 years by the time the Greeks began to study it systematically, in the fourth and third centuries B.C. This tradition began in Sumer and was greatly advanced in Babylonian times. Numerical calculations and the ability to predict the periodic appearances of planets and certain stars existed by the 2nd millennium B.C. But for various reasons, it took longer for measurement to evolve into the use of mathematics. Indeed, this seems not to have happened until after 750 B.C. Prior to that time, the nightly heavens were observed and recorded for two main purposes: 1) identifying and reading omens, of which there were a great many, leading to creation of constellations and the zodiac; and 2) producing agricultural calendars and almanacs. More precise, mathematical astronomy came from the first of these – just as alchemy, the manipulation and transformation of earthly substance, became the source of chemistry, so was astrology the origin of much astronomy (use of the term "superstition" in this context betrays, again, a modern bias).

The oldest artifacts, dating from about 2500 B.C., are fascinating to see. They are little cylindrical seals and larger stone bas-reliefs depicting the gods in association with the Sun, Moon, and Venus. These gods, as bulls, lions, and other animals, may well represent early depictions of constellations. By Babylonian times, we see in such imagery the association of the other planets with certain animal signs, such as the dragon for Jupiter and panther-head for Mars and a serpent with the Milky Way.

These were astrological, or divine, signs. Culturally speaking, planets and stars, meteors and comets, supernovae and eclipses were all read as omens of coming events. Astrologers were relied upon as prophets in lower case: kings consulted them on a regular basis about (for instance) whether to go to war, whether their next child was male or female, or where to locate a new palace. From the beginning, to aid their cause, astrologers looked for regularity in the heavens and so kept records, compiled into archives, about celestial motions. Observations were recorded in different "diaries" extending up to about six months and including daily and monthly tablets, where they were often mixed with meteorological descriptions. Since eclipses were understood to be omens of potential bad times (or worse), the ability of eclipse prediction added greatly to the status and standing of astrologers.

Because of centuries of accumulated observations preserved in archives, the later Babylonians (ca. 750 B.C.) were able to estimate many phenomena with great accuracy. For example, the length of a synodic month, between two full moons, was known to within a few minutes of its real length and by roughly 500 B.C. to within a few seconds. Astronomer/astrologers also determined that 235 lunar months are pretty much identical to 19 solar years (known as the Metonic 19-year cycle).

Astrologers, whose work it was to study the large amount of collected celestial information, came to perceive finer patterns over the decades and centuries. Sometime between about 700 B.C. and 575 B.C., they discovered the so-named Saros Cycle of 223 synodic months, within which lunar eclipses occur mainly every six months, with a few after five months, allowing for a predictive model to be derived. This was then extended by analogy to solar eclipses.

Almanacs also looked to comprehend the motions of the Sun and Moon, in particular, for the sake of calendar-making. Like other ancient peoples, the Mesopotamians used a lunar calendar. But this had to be adjusted using "leap" months, as we call them today, so that the lunar months remained regular within every solar year (marked by the rising and setting of certain stars corresponding to the seasons). Once again, that is, we find the Babylonians coming up with methodological rules, technical generalizations of a sort, without the dimension of theory.

What the Babylonians never seem to have attempted was a systematic theory or geometric model to explain planetary motions. In a way, however, this would be too much to expect. Again, their fundamental understanding that the heavens, as the realm of deities who produce and impact events on Earth, makes it far more imperative to learn the signs of their intent, the repeated signals of their anger, beneficence, or caprice.

Still, no less a modern astronomer than Pierre-Simon Laplace stated that the seven-day week counts as "the most ancient monument of astronomical knowledge." What did he mean by this? It is something very basic. The Sumerians seem to have been the ones to identify seven successive days with the seven visible bodies of the solar system – Sun, Moon, Mercury, Mars, Venus, Jupiter, Saturn (the Earth was the center, and the next planet, Uranus, would not be discovered until 1781 by William Herschel, working with a telescope). The Hebrews, according to the Bible, also claimed a seven-day week, as told in Genesis I, with the final day as Sabbath, God's day of rest. Did the Hebrews derive this scheme (minus the story) from the Sumerians?

In a dry, desert climate, the heavens at night are a vast manuscript, stretching from one horizon to another, shimmering with patterns and meanings. Mesopotamians, lacking the regularity of a Nile-type river, focused their perceptions of order in the skies. The order they found rules the seven-day working of the world today.

The great library of Ashurbanipal

Alexander the Great is said to have gained the idea for a great library in his new city of Alexandria after learning of the renowned collection that had once existed in the city of Nineveh. This was the library of the Neo-Assyrian king Ashurbanipal, who reigned from 668 B.C. to 627 B.C., during the twilight height of Assyrian power.

Ashurbanipal, literate and highly learned, was not the first to build a large library. It was a natural outgrowth of the tendency among Babylonian scribes to create archives, not least for astronomical observations and predictions. Libraries seem to have emerged as a sign of a ruler's power. But Ashurbanipal's collection was on a wholly new scale, backed by an imperial desire to gather wisdom from all parts of the Neo-Assyrian empire, from Egypt to Babylon, and in every field of knowledge.

To achieve this, Ashurbanipal sent scribes to search out, collect, and, if necessary, copy all important contemporary and ancient texts. Almost certainly some amount of translation was involved. The king also confiscated texts from other collections after military conquests. All told, the original vision seems to have been largely fulfilled. We know this because of the many thousands of clay tablets, as well as fragments of many others, that have been recovered from the library site at Nineveh.

Preserving the past in this way, at a single site, perhaps with writings catalogued in some way, may have offered scholars of all kinds a magnificent resource. If open to scholarly use, it would be vast nourishment for future advances. Had it been preserved in its original totality, or nearly so, we would have today a fairly complete picture of Mesopotamian science. Given the enormous importance of this science to the Greeks and those who came after, such a picture would be a magnificent possession.

Unfortunately, only a few decades after the death of Ashurbanipal, Nineveh was utterly razed to the ground. The Neo-Assyrians were widely known as cruel and brutal rulers. The Old Testament (in the prophecy of Nahum) describes them as without mercy and compassion, a blight upon the Hebrews and an example fated to be annihilated by God. Destruction, however, came from a huge force of Babylonians, Medes, and Scythians who rose to end Neo-Assyrian hegemony and laid siege to its capital in 612 B.C. After several months (according to Babylonian chronicles) of fruitless attacks, they received help from the Khosr River, a tributary of the Tigris that ran through the city and went into sudden flood. Assyrian engineers appear to have underestimated the Khosr, and the city paid for it dearly. So high were the waters that they smashed through the flood gates and washed out part of the inner and outer city walls, creating a breach for the enemy to swarm inside. The besiegers gave no quarter or mercy. Indeed, the Neo-Babylonian dynasty that overthrew the Assyrians were even more cruel than their predecessors, laying waste to many cities and erasing the entire Assyrian people from the pages of history. So brutal and total was the destruction at that first siege at Nineveh, that when Alexander the Great fought a battle nearby three centuries later, he had no inkling any city, let alone a great imperial capital, had ever existed there. Only in 1849 was it re-discovered.

Here the story turns to tragedy of a different sort. When the library, with all its thousands of tablets, was unearthed and first excavated in the 1850s, no record was made of its contents. No technical catalogue or precise list of contents, such as the Sumerians and Babylonians might have compiled themselves, was ever attempted. Still worse, when the trove of tablets was eventually shipped to Europe, along with texts from other sites that had been recently opened, they became mixed with each other, making it nearly impossible to separate out the original materials of Ashurbanipal's library. History, in other words, has deprived us twice of this collection.

The texts sent back are now in the British Museum. They number more than 30,000. Among them are the oldest version of the famous *Epic of Gilgamesh*, as well as numerous astrological and mathematical texts. Many were baked hard in the fires that leveled the city. In all likelihood, these fires consumed large numbers of papyri from Egypt. It must seem ironic that the most primitive technology of writing survived this disaster, while the more advanced form, paper and ink, which the world has come to rely on, did not.

Of contracts and codes

Above all, the Sumerians were traders. So it shouldn't shock us that yet another invention of their civilization was the written contract, "signed, sealed, and delivered," as the saying goes. What made this possible was a technological-artistic product known as the cylinder seal. Dating from as early as 3500 B.C., it is a cylinder of stone or sometimes bone, ceramic, wax, or other material, no more than a couple of centimeters high, carved with a bas-relief of images specific to a particular merchant or commercial partnership. When this cylinder was rolled over a wet clay tablet, it left a signature seal. Worn around the neck of a hired scribe or merchant, these seals reveal an imagery that is hugely varied – hunting scenes, heroic battles, monsters and fabulous creatures, gods, animals, rulers, and more, often with writing. There are even characters from Indus script, proving direct contact with India. Even from the 3rd millennium B.C. images can be strikingly naturalistic, with bulls showing musculature and leg joints, neatly observed.

Contracts were part of the total social order, but kingdoms and then empires demanded laws, rules of behavior and justice. The most comprehensive record we have of such laws is the Code of Hammurabi, dating from the early 18th century B.C.

This most famous of ancient Near Eastern documents, discovered in 1901 at Susa in modern-day Iran, was a stele of black diorite on which were inscribed no fewer than 282 laws, portraying a mixture of harsh, calculated, and ethical rules and punishments (Figure 3.5). For a number of offences, from robbery to murder, the penalty was death. Slavery was another common punishment for those who committed crimes or couldn't pay their debts. Many laws concerned tenant farmers, their obligations and contracts regarding fields, gardens, and crops; others dealt with rates and fees for various services. There are "eye-for-an-eye" laws (if a man break another's bone, his bone shall be broken) and laws on public responsibility (for builders of houses, slave owners, herdsmen). The greatest number of rules, however, concern families, relations, and property ownership among

Figure 3.5 Stele bearing the Code of Hammurabi, showing Hammurabi (left) receiving the code (system of laws) from the god Shamash (sitting). The stele is on display in the Louvre Museum in Paris. © World History Archive/Alamy.

husbands and wives, fathers, sons, and daughters. Some protect wives against adulterous and uncaring spouses. Others protect sons or their betrothed against capricious and lascivious fathers. Yet, "if a son strike his father, his hands shall be hewn off."

What, then, does any of this have to do with science? In both the prologue and epilogue to the list of laws, the stele states that Hammurabi (who speaks in the first person) is the great conqueror of evil,

> Hammurabi, the protecting king am I. I have not withdrawn myself from the men, whom Bel gave to me, the rule over whom Marduk gave to me, I was not negligent, but I made them a peaceful abiding-place . . . With the

> mighty weapons which Zamama and Ishtar entrusted to me, with the keen vision with which Ea endowed me, with the wisdom that Marduk gave me, I have uprooted the enemy above and below (in north and south), subdued the earth, brought prosperity to the land, guaranteed security to the inhabitants in their homes. . . .

Hammurabi doesn't just claim authority and righteousness. He is saying his rule, determined by the gods, is obedient to the laws and necessities of the cosmos. And because of this, he has been given the edict to wield these forces in ways that benefit and protect his people. Hammurabi's code was more than a list of rules. Establishing justice, keeping relations between all members of society firmly in balance was to bring the kingdom of man into alignment with that of nature and the universe.

Part of achieving any alignment between man and nature required knowledge of the universe and its powers. It required, in other words, a king or emperor who would act as a great patron of science and technology in the ancient world. Hammurabi certainly filled this role. It was under his reign that astrology – which must not be mistaken for pure mythology – and thus astronomical observations advanced a considerable degree and moved to the center of kingly concerns. It was in his reign, too, that engineers were put to work at a fever pitch, rebuilding and enhancing the city of Babylon as capital of the new empire. Hammurabi united all of Mesopotamia and extended the empire to the Mediterranean and the Persian Gulf, thereby gaining control over nearly all of the Fertile Crescent. His purpose in this was to control all agriculture "between the two rivers," trade along them, as well as rich mines to the north and east in modern-day Iran.

Above all, Hammurabi was known as a great builder and supporter of public works. From many descriptions, we can believe that Babylon in the time of Hammurabi was the most impressive, elegant city in the region. Accounts suggest that Babylon – which, in Akkadian, means "gate of the gods" – was a great square bisected by the Euphrates, whose banks were built up far above flood stage, possibly by walls and terraces that may have later been turned into the famous hanging gardens. Water from the river was diverted around the entire city to fill a great moat, that flowed like a tributary. A massive bridge, able to bear a large procession, spanned the river, which was full of boats arriving and departing from the trading docks. Water was drawn into subterranean canals that fed parks and gardens and helped cool the inside of palaces and villas during the hottest months. Babylon's walls of fired brick were perhaps 10 m thick and over 30 m high – Herodotus, many centuries later, describes them as nearly twice as a tall. In a great paved square sat the ziggurat, reputedly 90 m on a side and 20 m tall.

The peace that began Hammurabi's reign did not last. Despite his intent to be a righteous lawgiver, the king did not build a sturdy bureaucracy and power structure to unite the empire. Its borders soon came under attack and within 50 years of Hammurabi's death, it fell apart and would not be recreated until the kingship of Nebuchadnezzar I (1126–1104 B.C.).

The hanging gardens (of Babylon)

These gardens were known as one of the Seven Wonders of the Ancient World. They were declared as such by Greek and Roman writers. But there is a problem. These authors all report on the basis of hearsay; those who wrote earlier about the city of Babylon do not mention them. A 20th century German team, who spent 19 years excavating the ancient site, found not a single text, inscription, image, or monument even hinting at the ancient wonder.

The story of the hanging gardens, however, is hard to let go. It is both romantic and scientifically fascinating. The telling of it is attributed to a priest from Babylon itself, Berossus, who lived sometime between 330 B.C. and 250 B.C., just after the city fell to Alexander the Great. The story holds that king Nebuchadnezzar II (ruled 605–562 B.C.) took as his wife Amyitis, daughter to the ruler of the Medes in Persia, who grew depressed in the stark desert kingdom, so different from her homeland. Nebuchadnezzar had built a great garden with trees, bushes, flowers, and other plants from Persia.

To do this, his gardeners would have been tasked with many innovations. They needed to make expeditions to Persia to determine which plants would be able to best survive in the new environment and what soil conditions they required. They are reputed to have built multiple, stacked terraces for a wide variety of plants, permitting some to grow with minimal trimming and hang over terrace edges. The description in Diodorus Siculus says that "streams of water emerging from elevated sources flow down sloping channels . . . irrigate[ing] the whole garden. . . . The water machines [raised] water in great abundance from the river, although no one on the outside could see this." A river bank location, moreover, would bring a more cooling, moist microclimate. Over time, with continued care, a grand and exotic arboretum suspended in air above the cooling river could have resulted. Such a creation would truly have been wondrous.

Perhaps it is not all a myth. Evidence may be lacking in Babylon, yet it has been found in abundance to the north, at Nineveh. Here, Babylonian and Assyrian writings suggest that the ruler of this city, Sennacherib (ruled 704–681 B.C.), built a garden in the shape of a terraced palace that recreated a lush mountainside and was a "wonder for all peoples." It had walkways through exotic trees and plants, with small streams running continually. Sennacherib's own writings speak of a water-raising screw – centuries before Archimedes' famous invention – made using a new technique for casting bronze, which operated "all day" and thus possibly irrigated the garden. A sculpture found at Nineveh depicts a garden built upon a bridge with several arches, similar to the description given in Greek and Roman writings for the gardens at Babylon. This information, furthermore, gains some significance in the context of Sennacherib's own rule. Making Nineveh his capital, he built it into a metropolis of grandeur and brilliance, with canals and aqueducts, wide streets, many monuments, and his own magnificent palace with paving stones of lapis lazuli. He had an interest in scientific matters as well, and imported exotic plants, such as cotton (probably from India), and cultivated them in urban gardens.

The fame of this city was such that it came to be known as the "New Babylon." Indeed, Sennacherib even renamed the various gates into Nineveh after those of Babylon. Thus, a transfer seems possible: the wonder of the hanging gardens may well belong to both Nineveh and "Babylon."

Medicine and public health

In the Library of Ashurbanipal, archeologists have found as many as a thousand clay tablets related to medicine. At least 900 other tablets from a variety of sites provide information on methods of treatment for various ailments. This means diagnoses, remedies, medicines, incantations, spells, and prognoses. Many of these texts, like those in Egypt, were used for training and easy reference. They give us, in other words, a window into the practice of medical work at a beginning, everyday level.

Such work was truly diverse, and its burden on the memory no small thing. Hundreds of different drugs are mentioned, and there are long lists of plant and mineral ingredients. Thus it is probable that medical "books" were used as reference works for practicing doctors. Such "books" give evidence for two types of professions involved in treating illness. One of these was the physician in the more modern sense; the other was closer to an exorcist. Since many diseases were believed to be caused by demons, ghosts, and curses, incantations had to be learned too, and these could be in the form of dialogues between major gods that sought to invoke divine presences for the exorcism (e.g. "[T]he Seven were born in the Netherworld . . . and have approached here . . . Go, my son Marduk: . . . along with the august Eridu incantation formula of purification, apply fire to the tip and base, so that the Seven do not draw near to the patient."). From existing cuneiform tablets, it's clear that demons or spirits could be associated with trouble in individual organs or with the body as a whole.

The most extensive writing is called the "Treatise of Medical Diagnosis and Prognosis," and consists of some 40 tablets with a listing of many hundreds of conditions and illnesses. These show the use of empirical knowledge and divination was similar to that in Egypt. Three types of healers existed: 1) physicians, who performed diagnoses, used actual medicines, and treated wounds; 2) preparers of medicines, who understood the use of herbs and who also knew how to bandage wounds, set bones, and treat routine injuries; 3) priests or diviners, who would use incantations, animal sacrifice, and exorcism. Of these three, the physician was the primary care person. Yet there was also frequently overlap in the work performed by all three.

Illnesses were as varied as those in Egypt. Infectious diseases, such as malaria and typhoid, were well known. Contagions were well known, as were a wide range of ailments such as cancer, tuberculosis, jaundice, kidney stones, and various kinds of cardiovascular disease. A unique dimension to Mesopotamian medicine was its recognition of mental illness: there are, for example, a number of references to "depression" and its incapacitating effects.

Disease wasn't given a theoretical explanation. The best we can surmise is that the Mesopotamians believed it was mainly due to possession by demonic or punishing spirits (from the gods) that would reveal themselves through a particular symptomatology, i.e. set of bodily signs. But there were other concepts for causes for disease. Some ailments, as we've noted, were due to non-physical "infections" by ghosts and spirits. Others came from certain environmental conditions: coldness or dryness, poisonous air or water (e.g. from dead animals), and bad diet. In nearly all cases, however, diagnoses were made strictly from observed symptoms.

Physicians, known as *asu* (herbal remedies and related treatments) and *ahsipu* (exorcists), were indeed careful observers and gatherers of information. Methods of the *asu* included visiting patients in their homes and asking them, and any others who had attended them, a series of probing questions. Was there was a history of family illness; had the patient recently visited places where diseases were common; what types of behaviors and activities did the patient normally engage in; what type of sexual history did the patient have? When examining patients directly, a physician would follow a certain regimen: touch them to determine temperature or levels of pain or how fast the pulse beat in the temples; inspect color, movement, breathing, and note the appearance and smell of urine and feces. A detailed and complex terminology existed to record all observations. An example, describing a fever spike, possibly for malaria:

> If [fever] falls upon him for two days and then afflicts him on the third day and when it afflicts him, he continually becomes rigid [and then] has a trembling, his limbs continually hurt him, his hands and his feet are cold, [and] afterward fever rides over him everywhere at once and sweat falls upon him and then he finds relief, *stibit sadi* afflicts him.

Treatments, of course, depended on diagnosis. Herbal medicines were applied in most cases to allay symptoms, not necessary to cure. Though established treatments existed for various disease symptoms, a physician would continue to observe a patient once these were administered, and if they didn't seem to be working he would try another medicine or medicines. A degree of experimentation, therefore, was involved. Wound dressings were made from plant resins such as myrrh, animal fat, and alkali, producing a substance that would have suppressed infection. Dressings were changed often, suggesting knowledge that infection would otherwise set in. Umbilical cords were cut with a "sliver of reed" acting as a disposable instrument. Bandages and clothes worn by a patient during certain illnesses had to be burned. A high degree of cleanliness, therefore, was understood to be a preventive measure regarding illness. Disease cures, meanwhile, in cases where they were deemed possible, mainly depended on rituals performed by the priest/diviner. Such rituals were intended to placate or evict the offending spirit. In addition to incantations, some rites involved the use of figurines, libations, and charms like special necklaces made of a leather pouch carrying a combination of herbs.

Herbal medicines included many substances. More than 250 plants and 120 mineral substances were known and used. Many of the herbs were aromatic when reduced to their essential oils, and this might well have been a preferred property for medicine generally. From the Sumerians on, such oils were extracted by filling clay pots with the relevant herb, adding water, stuffing wool into the mouth and then heating the mixture until steam was given off, carrying the produced oils into the wool, which would then be squeezed to extract the final product. Such a basic process was also used for fumigation, another form of therapy, along with simply placing the herb(s) on heated coals. Among the herbs used for this purpose were datura, claviceps, mandrake, and poppy – all with psychoactive properties – and also chamomile, fennel, henbane, saffron, turmeric, and myrrh, whose odors had soothing properties.

Plant oils were combined with various other liquids – beer, wine, animal fats, honey, milk of different animals. Colloquial names were given to a fair number of materials and drugs, such as "lion's fat," making it very difficult to determine just what they were. Plants chosen for drugs often had either antibiotic or antiseptic properties. There were remedies not only for serious illnesses but for what have been often called the mundane "ailments of civilization," such as constipation, occasional diarrhea, acne, hemorrhoids, and bad breath. Generally speaking, with regard to herbal remedies, one of the most commonly used ingredients, mentioned as early as the end of the 3rd millennium B.C., came from willow bark, which is rich in salicylate, the primary component of aspirin (acetylsalicylic acid). This remedy seems to have originated in Sumer and was transferred to Egypt and other regions thereafter.

As in the case of Egypt, the details of ancient Mesopotamian medical practice are impressive. It is worth quoting two scholars who have studied these details to the highest degree and published their findings as recently as 2005 (see the book by Scurlock and Andersen in the bibliography for this chapter): "It is no exaggeration to say that the skill of ancient Mesopotamians in diagnosis and therapy was only surpassed in the late nineteenth century" (p. 12). This is high praise indeed for those overworked, house call physicians who lived four millennia before Louis Pasteur and the germ theory of disease!

No less impressive, the Babylonians under Hammurabi had something akin to a managed health care system. Physicians used a sliding scale for payment of services, based on the ability to pay and on different set rates for various surgeries. A wealthy person should remit ten silver shekels for successful treatment, a craftsperson five, and for a slave only two. Owners were thus required to pay for the healthcare of their slaves. There was also a scale of liability associated with malpractice. The Code of Hammurabi is quite specific about all of this. It sets out the prices physicians could charge, making it clear that these depended on a patient's social status and income level. Patient rights were publicized, and there were severe penalties for physicians or surgeons who provided improper care or committed malpractice. In case of complaint from a patient, the government had the right to investigate. The following are some of the specific laws set down in the code:

> 215: If a physician make a large incision with an operating knife and cure it, or if he opens a tumor (over the eye) with an operating knife, and saves the eye, he shall receive ten shekels in money.
> 216: If the patient be a freed man, the surgeon receives five shekels.
> 217: If the patient be the slave of someone, his owner shall give the physician two shekels.
> 218: If a physician make a large incision with the operating knife, and kill [the patient], or open a tumor with the operating knife and cut out the eye, his hands shall be cut off.

What of prevention, via public health? Like Egyptians, ancient Mesopotamians were better at keeping themselves clean and preventing the spread of illness than were most 19th century Europeans. Hands were washed before eating, using plant-derived alkali soap, and baths were taken regularly. Medical writings make some interesting statements along these lines: "If he enters lavatory, his hands will not be clean"; "If he rubs his eyes with his unwashed hands, as long as he lives, his eyes will be sore." Houses were swept clean, using palm fronds, and were supplied with bathrooms that held a basin for washing and some type of toilet that would convey waste into an actual underground sewer system draining to the river. Because of this practice, cities located downstream learned to get their fresh water from wells.

Mappa mundi: a map of the world

The power of empire is the power to control space and to conceive a world ruled from a single center. But it is also the power to catalogue, record, and document geography on the basis of many thousands of observations. Did most great empires of the past, like those of the modern period, create maps? We don't really know. But why would they? To codify the reach of their authority, but also to show their vision of the greater world at whose nexus they (naturally) exist.

Such a map by the Babylonians is shown in Figure 3.6. Though it dates from the 5th century B.C., it appears to be a copy of one nearly twice as old (9th–8th c. B.C.) that, in turn, was based on a much earlier version dating from the first Babylonian period (1800–1100 B.C.). That this clay tablet has often been called the oldest known map of the world – all earlier maps presumably showing more local features – seems less important for us than its complex mixture of geographic, topographic, and mythological (religious) elements. These tell us some essential things about the scientific imagination in this culture, at this time. Still more, they highlight certain aspects about maps that have continued down to the present. The clay tablet was discovered at Sippar, about 60 miles north of Babylon and currently resides at the British Museum.

We might first notice that the image presents a birds-eye view, thus a flat projection of the earth. While there is a hole in the center, presumably representing the

Figure 3.6 A Babylonian map of the world. The map dates from 700–500 B.C. yet represents a view of the world that is likely much older, from the early-mid 2nd millennium B.C. © www.BibleLandPictures.com/Alamy.

global axis (there may have been an inserted stick or metal rod to cast a shadow and show the sun's position), there are no other topographic features shown in relief, i.e. as raised or sunken areas on the clay. Thus we are looking at flattened, symbolic type of image. What does it show, geographically?

There are three domains: an inner area with a number of symbols, a circular belt, and an outer area that originally consisted of seven or eight triangles radiating from the circular band. These three domains represent major portions of the

Earth. The interior realm consists of the known world: there are mountains at the top, marshland at the bottom, the Euphrates river running vertically as a band, from the former to the latter, and a number of named cities along the margins. There is the hint of a channel curving off to the right of the lower part of the river, connecting with the circular band. Babylon itself can be seen as a rectangle in the upper center, divided by the Euphrates. This alone tells us that the top of the map has a direction about 45 degrees west of north. This is both the direction from which a favorable wind came (sent by the goddess Ishtar) and also the orientation of the Euphrates through the empire's capital. As shown in the accompanying interpretation, several places are named on the map, including Assyria and Armenia. These are in their proper places, relative to the mountains at the top, which represent the source of the Euphrates in modern-day eastern Turkey. Khabban, on the other side of Babylon, correlates with Yemen, which is far more distant than Assyria. So we are looking at a diagrammatic map; scale and distance are less important than relative position.

The circular band, meanwhile, is described by the text on the tablet as the "bitter river," meaning the ocean. For the Babylonians, as for most pre-modern peoples, the edges of the known world were lapped by a great circular ocean. In this case, we can guess that they associated it with the Mediterranean to the west and the Persian Gulf to the southeast, with vast connections between these to the north, east, and south. Between this great enclosing ocean or "river," as well as the Euphrates and its marshland delta and channels, water defines a major reality of the Babylonian world. Since Babylon was a trading empire, this makes perfect sense. Yet it expresses something more, too. These people perceived that the land, as created by the gods, was not merely encircled but divided up and given meaning by bodies of water, that "geography" itself was determined by these realities, with cities and regions bordered and defined by them.

Beyond the boundary of the great bitter river or ocean lies an uncharted and fantastical domain of seven or eight islands. Great heroes have been here, but no other mortals, and there is but little record of what was seen. The preserved text, which includes the back of the tablet, describes the last five of seven regions. Some of these descriptions are very interesting. For the third region, "the winged bird ends not his flight," i.e. he cannot reach it. The fifth, lying due north, is a land "where one sees nothing" and "the sun is not visible." The seventh, in the east, is "where the morning dawns." Thus, the third region lies too far across the waters, while the fifth suggests the polar regions in winter, and the seventh reminds us immediately of the German word for "the orient" – *Morgenland* ("morning-land").

So, again, as often with the Sumerians and Babylonians, we find ourselves on ground that is both strange, distant in time, and yet somehow familiar. We may think, that is, we have advanced immensely, even infinitely, beyond such primitive representations of the world. Just consider the unparalleled precision we can achieve with maps today, not to mention the innumerable types of information we can add to such maps or use as the basis for creating them. But when we look carefully at any such image, we can see that it is as much a symbolic representation as a technical one – it is full of signs showing us, for example, latitude and longitude, plains as light green, forests as darker green, mountains as brown, rivers as blue, oceans as a different blue (possibly graduated in darkness with depth), deserts as yellow. We find the names of certain features (and not others), elevation numbers, small islands drawn in at many times their actual size. None of this exists in nature, of course.

Even the most accurate maps today, generated by the most advanced scientific instruments and software, are full of symbolism. Like the Babylonians, we draw cities as round dots, political boundaries in thick lines, and water as fairly clear, open areas. We choose a country or region as a central reference point and plot the world around it.

Concluding words

During the first century of modern archeology, up to the 1960s, it was generally believed that religion ruled all aspects of ancient society. Only with the rise of Greece did knowledge of the natural world and related technology become an important element of civilization. We now know that this idea was wrong. With the exception of Egypt, early civilizations were not at all saturated with religious sensibilities and did indeed pursue understandings of nature separate from spiritual purpose.

For this truth, we need to look far as we have done in this chapter, though at an introductory level. And yet there are powerful signs elsewhere that nature was worthy of study and observation for entirely secular reasons. For this, we might consider the image of Figure 3.8. Assyrian kings imported lions from Africa in order to release them under controlled circumstances and hunt them, as a show of royal prowess. In this image we find a lioness, dying in agony, an arrow in her spine having disabled her hind legs, which she drags like lifeless stalks. The muscles in her shoulder bulge and strain, her head is raised in a roar of pain and rage, her ears pressed back, claws gripping the earth. To the modern eye, it is an image of great pathos and of cruelty: we feel the fatal misery of this beautiful, broken animal. Yet nothing could be further from the aim of the artist. This was to show the power of a great king, who could destroy such a beast of killing fury with his bow. It is, in fact, the stunning naturalism of this portrayal that spans the 26 centuries dividing these two responses, a naturalism that originates in unburdened study of reality.

From the cities of Sumer and Babylon, thousands of clay tablets relating to science and technology have been found, deciphered, and seen to show no signs of supernatural aspect. The gods seem to have often left man to do things on his own. Better said, the Mesopotamians were practical as well as religious and may also have indulged a curiosity about the world separated from either of these domains of demand. We know that scientific knowledge was transmitted from one generation to the next through teachers and through texts that were distinctly non-religious. Much was learned by means of apprenticeship, whether in workshops or on visits to patients. Little doubt must there be that apprentices had to acquire a specialist vocabulary and discourse, knowledge of many materials, facility with

Figure 3.7 Dying Lioness, Palace of Ashurbanipal, Nineveh, Iraq, bas relief panel, limestone, c. 669–633 B.C. © Ivy Close Images/Alamy.

procedures for mixing and making various substances, familiarity with tools and techniques, all of which had a stronger element of required pragmatism than spiritual devotion. We could assume that such concentration on the practical, at the expense of religion, was required for continued advancement. This too, however, would be presumptuous.

Note

1 The Euphrates is called an "aggrading" river. It lies in an actively subsiding basin (Tigris-Euphrates Basin), which, over time, reduces the overall energy of the river by lowering it nearer to sea level. As it loses energy, the river cannot carry all of the sediment it previously did and so deposits some of it along its bed. This, then, raises the level of the river.

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4 Indian science

A great blending of traditions

> O shakers of the earth, moved by whose wisdom, whose design? . . .
> When what is strong ye overthrow, and whirl about each ponderous thing . . .
> Your course is through the forest trees of earth, and through the fissures of the rocks. . . . Even the earth herself listened as ye came near, and men were sorely terrified.
>
> *Rig Veda*, 1.1.39

> He who disparages this universally true science of astronomy . . . loses his good deeds and his long life.
>
> Aryabhata, *Aryabhatiya*, Gola: 50

For most of human history, natural science and religious belief were close colleagues. In the Scientific Revolution, too, religious content or context was common. Proof is easy to find: Newton himself wrote, "This most beautiful system of the Sun, planets, and comets could only proceed from the counsel and dominion of an intelligent and all-powerful Being." Science was inquiry into the creative work of the Creator; knowledge of this work meant a deeper knowledge of God. Newton was hardly original in this idea, of course. Yet the notion that science brings us *closer* to the divine was likely not native to Christianity. It had other sources, in very different times and places.

One of these was ancient India. "Whoever knows . . . the movements of the Earth and the planets in the sphere of the asterisms, [travels] through the paths of the planets and constellations and goes to the higher Brahman [God]." So says the *Aryabhatiya*, the most influential work of early Indian mathematical astronomy, written in the 6th century C.E. The suggestion poses nothing less than an alternate path to salvation: to achieve nirvana, you may choose to follow the rituals, prayers, fasting, etc. decreed by holy doctrine, *or* you can spend the time and effort needed to learn the science of the heavens. In ancient India, knowledge and religious belief were united: the highest states of consciousness required much knowledge about nature and the world.

We find this confirmed in the *Vedas*, "Books of Knowledge," forming the original scriptures of Hindu beliefs. These are an extraordinary collection of teachings, first compiled and written down about 1500 B.C., with further recording down to 500–300 B.C. Before this, and also well after, they were transmitted orally, and there is no way to know how truly ancient they may be. They include many thousands of poetic verses – hymns, chants, prayers – that speak about the nature and powers of the gods, the methods by which they must be worshiped, and the universe they created, including its composition, movements, and the dimensions by which the gods measured it out and set it in motion. Richly metaphoric, the *Vedas* lend themselves to many levels of interpretation.[1] They have been the primary sources for Hinduism to the present day, and they were called upon as well at the dawn of another age. At the testing of the very first atomic bomb in 1945, J. Robert Oppenheimer, head of the U.S. effort to build such a weapon, quoted from the *Bhagavad-Gita*, "I am become death, destroyer of worlds. . . ."

The Sanskrit word *veda* means knowledge or wisdom and something more. In ancient Indian writings, *veda* also refers to a field of study, like *ayur-veda,* meaning "knowledge of life," or medical science. Meanwhile, Sanskrit is an Indo-European language, and linguists have found that *veda* comes from a root, *veidos* or ueidos, signifying to see or know. We find the same root in the Latin verb *videre*, meaning to see, look at, consider, and, finally, in our own modern word *video*. India, in short, is perhaps more important to the making of the modern world than we might have thought.

Background: Indus Valley civilization

The first great society of ancient India was not that of the *Vedas*, however, but instead that of the Indus River Valley, which exists today in Pakistan. Of the three great valley civilizations dating from the 4th millennium B.C., that of the Indus Valley comprises the largest, most expansive, and least understood. It is only quite recently that scholars have begun to discern connections between Indus Valley and Vedic cultures.

Archeologists have identified the first major settlement in this area as Mehrgarh, considered to be among the most important early Neolithic sites in the world. Discovered in 1974, the site shows evidence of a farming village dating back to 7000 B.C., this having developed into a small town of mud brick houses and plazas in which crafts such as metalworking, bead-making, and production of terra-cotta figurines were well-advanced by about 4000 B.C. There is much evidence (tens of thousands of artifacts!) that updraft kilns, crucibles for melting copper, glass making (for beads), and tools for jewelry production all existed by this time as well.

Mehrgarh actually lies about 120 km northwest of the main Indus alluvial plain, along a tributary, at the base of the Bolan Pass through the Central Brahui Range, Baluchistan (Figure 4.1). This location occupied a key point along a migration route, which became a major path for overland trade between eastern Iran and the Indus Valley. Contacts with people from as far away as northern Afghanistan and southern Central Asia were established as early as the late 5th millennium B.C. Long distance trade, in fact, seems evident from the presence of lapis lazuli beads, which can be traced to the Afghanistan-Tajikistan area.

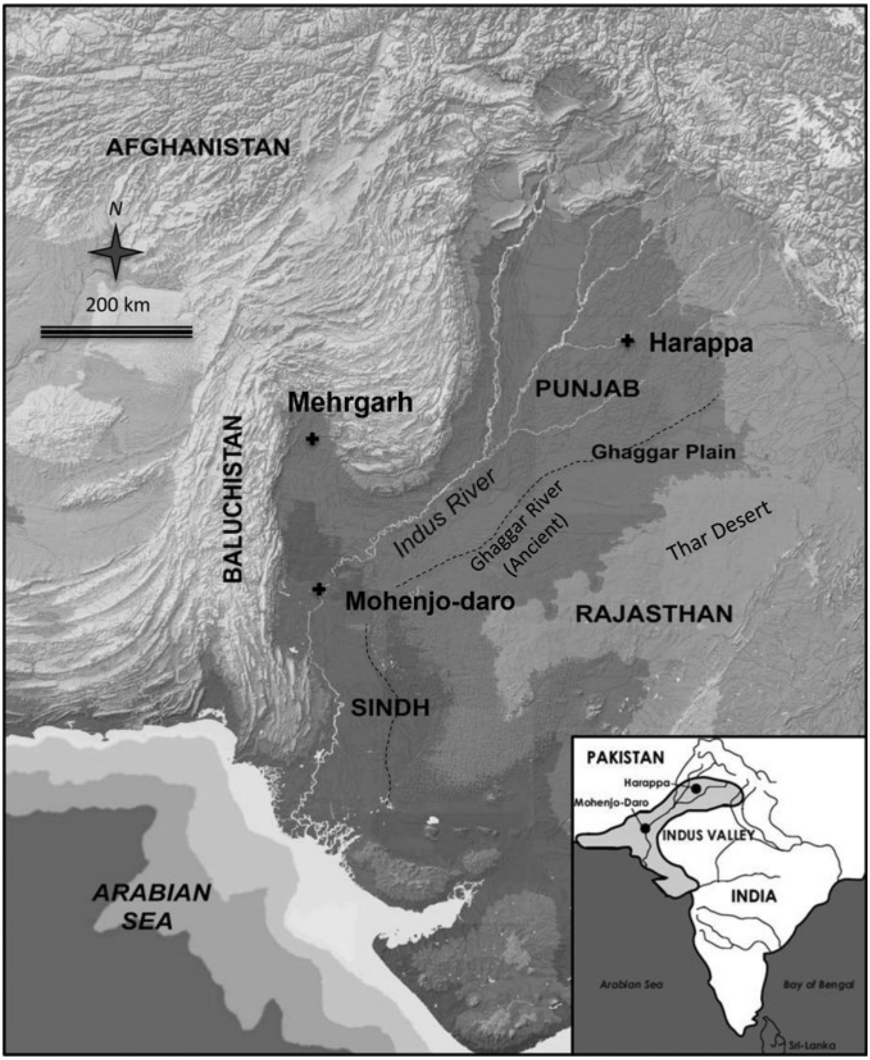

Figure 4.1 Regional map of Indus Valley, showing location of major ancient cities of Indus Valley civilization.

Mehrgarh can be considered the beginning of the Indus Valley civilization. From this town, Indus Valley peoples eventually spread over an area more extensive than Egypt and Mesopotamia combined (Figure 4.1). Over a thousand settlements have now been identified within this region. The first true cities arose about 2600 B.C., some 600–700 years after those in Sumer. By the end of the 3rd millennium B.C., dozens of large urban centers had come to exist. The two greatest sites, which appear to have served as principal hubs of trade and innovation, were

Harappa, located upstream in what is today the Punjab, and, 600 km downstream, Mohenjo-daro. As Harappa was the largest, most advanced city, it is often used to refer to the era and the people between 3000 B.C. and 2000 B.C. However, the Harappa site was occupied as early as 3700 B.C. and grew steadily to become a large town on a grid pattern by 3000 B.C.

There are striking, unique features to the Harappan Era. For one thing, it did not build a military culture. No evidence exists for warring among the cities, the rise of a conquering power, or an empire. Furthermore, like early Egypt, the economy did not depend on slave labor; it is likely there were no slaves at all. One possible reason is that enough basic resources existed for every major settlement, spread as they were across such a wide, fertile area. Walls built around cities had the purpose of keeping out animals and protecting inhabitants from flooding, not invasion. An economy that grew upon movements of trade, both local and international, helped create a singular level of cultural integration that may have curtailed aggression by depriving it of motive. Indeed, the nature of Indus cities argues for a more open type of society than in Egypt and Sumer, with a variety of groups having similar or more lightly differentiated status. Craftsmen, merchants, and artisans were everywhere, people that were productive and innovative in finding new ways to make new things, free of the demand to expend so much energy on forging weapons for a soldier class. The Indus, instead, was a society built upon the circulation and exchange of goods, ideas, and technology.

Like Egypt and Sumer, the Indus peoples created a system of symbols, apparently for written communication, sometime between 3300 and 2800 B.C. Like other early scripts, the system is richly pictographic (Figure 4.2) and suggests an evolution from pictures to symbols. Unlike these other scripts, however, no one has yet been able to decode it. How can this be?

For one thing, there is no Rosetta Stone for the Indus orthography. For another, the symbols are found on a limited number of surfaces – seals, pottery, a few tablets and tools – and in small numbers, ranging from one to six or seven. The great majority occur on small cylindrical seals, highly similar to those used by Babylonians. We don't find it as texts on clay tablets, on monuments, temple walls, statues, or other places that typically bear writing in other early cultures. The one possible exception may be a palm leaf manuscript found in Afghanistan in 2006 with some 62 symbols, of which at least 26 correspond closely to the Indus Valley corpus. Much analysis of this text is yet to be done at this writing.

Some linguists have proposed that the script doesn't represent speech in any way, but is a system of signs that may represent words or concepts. Others suggest that they have no important communicational function at all, a rather extreme view. Figure 4.2 shows that some symbols are clearly repeated and occur at any of several or more places within a line. From close examination of how they have been carved and spaced, it is apparent that they were written from right to left. It is also clear that there are distinct patterns in the occurrence of some symbols, even symbol combinations, but also that a good many occur only once. In other words, there seem to be rules applying to some signs but not to others. Overall, the Indus script differs significantly from all other ancient writing systems in a number

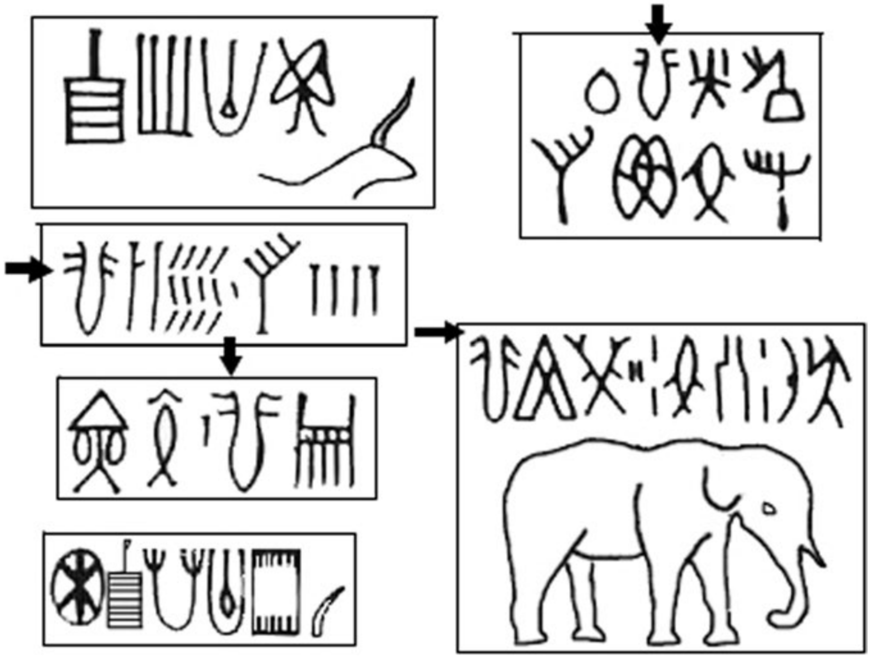

Figure 4.2 Examples of the Indus script, taken from clay impressions of cylindrical seals. Arrows indicate the same apparent symbol repeated in different lines. The script has not yet been deciphered, despite many decades of effort.

of ways. To date, no statistical or other computational analysis has been able to crack the Indus code.

Still, there are strong arguments in favor of the Indus Valley peoples having a system of writing. It is hard to fathom that the achievements of these peoples could have been possible without such a system. We could point to the extensive international trade that existed, the high level of architecture, engineering, craftsmanship, navigation, and more, as well as the integrated nature of the Indus civilization generally over such a large region. The necessity to keep track of goods bought and sold, property owned, debts, prices, inventories, and so forth would have been present from an early period. For now, we can't do much more than speculate. Unable to read this possible language, we have no ability to hear what the Indus people have to tell us.

From the ruins and reconstructions of towns and cities, the Indus region developed in a variety of settings. The earliest settlements, after 7000 B.C., were in valleys and adjacent plains to the west, due to strong summer monsoonal rains that brought destructive flooding to the Indus Valley. But as the monsoons shifted eastward and the climate began to dry, people moved into the major floodplains of the Indus and its tributaries. This was when annual flooding was less violent and excellent for predictable deposition of organic-rich silt. Settlements grew up along the Indus and a smaller, parallel drainage system roughly 70 km to the east, today called the Ghaggar-Hakra River. The two river systems retained year-round flow down to about 1900 B.C., coinciding with the peak era of agricultural development and urbanization.

The monsoons continued to move eastward, however. This second river system, which may correspond to the famous Saravati mentioned in the *Rig Veda*, became intermittent; many of its tributaries disappeared, forcing people to migrate eastward to the Ganges. Thereafter, the entire region became more arid: agriculture suffered, surpluses disappeared, and urban centers decayed. Before too long, only smaller towns and villages eventually remained.

During the peak Harappan period, urban growth benefited from advances that created a highly planned, well-organized, and materially refined culture. Trade was key, as we have said. There were trade connections along the rivers and tributaries; overland to the west and northwest (Afghanistan and Iran); and by sea to the Persian Gulf and from there possibly upstream on the Tigris and by land routes to Egypt and the Mediterranean. Indus artifacts and other evidence of direct contact have been found up and down the Persian Gulf, in Bahrain, United Arab Emirates, and Oman. There is even a possibility that Indus merchants built port "colonies" in some of these places to resupply their ships and to solidify further their routes.

Raw materials, such as stones and shells, as well as fabricated items like seals, beads, and jewelry, were both imported and exported. Manufacturing centers existed in most of the major cities, and these produced goods ranging from exquisite pottery, metalwork, and textiles to luxury items of many kinds. The Indus people thus built a complex economy with many working parts and a sophisticated organization that circulated goods simultaneously in many directions, near and far. Such is also shown by their agriculture: wheat and barley were cultivated fairly early, along with goats, sheep, and cattle, with some of the grains, like emmer, imported from Mesopotamia even before the Harappan Era began (i.e. before 3300 B.C.).

Nearly all the major trade routes were established before 3000 B.C. By about 2600 B.C., the larger settlements had been fully urbanized. New crops, such as sesame, peas, dates, and cotton, were now grown. These people had experimented both with local vegetation and non-native species. They did not develop irrigation systems, other than local reservoirs in drier years; they did not need to. Rainfall and floodplain regeneration were abundant enough. This, then, allowed their social organization and urban development to be based much less on agriculture and more on manufactured goods and related technology.

Indus technology and science

The largest cities of the Indus are remarkable in another way: they were planned. Urban planning on such a scale – for cities up to 150 hectares in size and populations up to 40,000 – can only intrigue us today. Where did the idea come from to conceive and map out an entire metropolis at such an early date, to figure out the resources needed, the labor required, the financial demands, and so on? Was it strictly religious in motivation? Did it involve a desire to build a human version of the cosmos? There is no real way to answer these questions as yet, without speculation. Perhaps if and when the Indus script is decoded, we will gain some answers. The religious dimension seems likely, though; all of the planned cities were oriented the same way, according to a single plan, lined up with the four directions of the compass.

Early settlements used sun-dried blocks of mud for building, but the innovation of brick kilns brought production of sturdy material that allowed cities to be erected, paved, and easily repaired. This directly parallels what occurred in Mesopotamia. But in India, fired bricks, using local clays but containing no straw or other ballast (which Mesopotamian bricks often did), proved to be extremely strong, as long lasting as the obelisks and granite monuments of Egypt. Some idea of the scale and strength involved with these bricks at Harappa comes from the documented story that in the 1850s, bricks from the site were carted away to help build a 100-mile railway between the cities of Multan and Lahore. Even so, a vast number of bricks remain at the original site in excellent condition. The number of bricks used, therefore, was extraordinary, reaching well into the hundreds of thousands, possibly millions.

These facts testify to mass production on a scale rivaling that of Egypt's stone quarries, but less monumental and more efficient. Bricks were given standardized dimensions. As many as 15 different sizes are known, corresponding to specific architectural uses, and have been determined to follow a fixed length-width-thickness ratio of 4:2:1. An assembly-line type of system for making these bricks must have existed; one group of workers excavating the proper clays, another measuring and shaping the raw block, perhaps using molds, yet another transporting masses of them to a centralized area where a large array of kilns were kept in operation by a final set of trained workers.

Kiln operators were not laborers but skilled workers who knew how to identify and cast aside mud blocks that would not bake well, to achieve and maintain required temperatures, regulate air flow, and decide a particular batch of bricks was "done." After cooling and further quality control (cracked, chipped, or malformed results being removed), the finished bricks would be delivered to the masons and their helpers. Whether these last worked from diagrams or from memory isn't known; no images suggestive of architectural plans have been found. Yet the whole gives us an idea of high-level organization dictated by technological production.

A number of cities were erected on paved platforms that leveled each site. Streets were laid out in a rectangular grid, oriented to the four principal directions using stars and the Sun. At Mohenjo-daro, for example, major avenues ran north-south and smaller lanes and connecting alleys east-west. Whether this was done for religious reasons isn't known. We should note, however, that such orientation would maximize protection from direct sunlight and thus keep much of the city relatively cool. More than 700 wells were dug to provide each neighborhood and many individual houses with a constant source of clean water. Various manufacturing centers were separated from residential and recreational areas. These centers involved the production of pottery, jewelry, statues and figurines, metalwork, and textiles (including the earliest known use of cotton).

All houses had functioning toilets and baths, as well as both indoor and outdoor kitchens (for hot and cooler weather). Most houses had an inner courtyard and were built with a number of interior rooms to create privacy. Based on sampling, the walls were covered with a gypsum-based plaster. Waste water, meanwhile, was routed to a covered drainage system beneath the paved streets. Waste was thus carried away from the city, suggesting one of the reasons why the Indus people were healthier than those in Egypt and Sumer, based on analysis of skeletal remains (it is not known if waste was conducted to nearby rivers). In short, both true urban planning and public sanitation begin with the Indus Civilization.

Most of the people who lived in these cities were not farmers but artisans, traders, merchants, and craftspeople. Those cities, like Harappa, Mohenjo-daro, and Rakhigarhi, that lay along rivers show evidence of granaries, warehouses, and extensive dockyards, testifying to a civilization constantly humming with commerce. At Lothal, a city site in the south near the coast, there are the remains of a large-scale canal and port connecting the city with the Gulf of Khambhat and Arabian Sea. It seems that some of these coastal cities acted like gateways to the larger culture, trading first with merchants from the Persian Gulf, then selling the foreign goods acquired to other urban centers upstream.

Indus artifacts at many sites along the Persian Gulf speak of ship-building technology at an advanced level. As in Egypt, there were ships and boats of many sizes, each built for a specific set of uses. Unique to the Indus culture, however, were ships capable of very long voyages, possibly 1,800 km, the distance from the mouth of the Indus to that of the Tigris/Euphrates. Navigation, thus basic astronomy, as well as currents and seasonal weather, were well known. Given the diversity of ports visited and the large distances between many of them, it seems more than likely that maps were created and regularly used.

An especially interesting conclusion: the long-distance voyages (to Oman, Iran, Bahrain, and Mesopotamia) that went on for more than a thousand years mean that much knowledge must have existed about marine life and coastal habitats. The Persian Gulf is less than 70 meters deep on average and is especially rich in shallow marine fauna – sea turtles, sea snakes, dugongs, whales, dolphins, more than 500 species of fish – and in species associated with coral reefs. Ship captains were almost certainly founts of natural knowledge, not just tales of the high seas.

At the same time, a mercantile society requires a dependable system of weights and measures. Indus people developed a uniform system of this kind that was highly precise and employed throughout the entire cultural region. Weights were arranged in base 10, based on units of about 28 grams. These were made out of limestone and, in the smallest sizes, ivory, beginning at the large end with 500 units, followed by 200, 100, 50, 20, 10, 5, 2, 1, 0.5, 0.2, 0.1, and 0.05. The small end of this scale was probably used to weigh beads and gem-like stones for jewelry and ritual decorations. Weights themselves were rectangular and cubic. Scales on which they were used were likely made of wood, not metal, and probably simple in design. The Indus system appears to have been unmatched in the ancient world. Samples of these weights have been found well to the west, at sites along the Persian Gulf, implying that the system was adopted by other peoples.

Vedic culture and science

Carl Sagan once pointed out that "Vedic Cosmology is the only one in which the time scales correspond to those of modern scientific cosmology." He did not mean that modern physics and astronomy lay hidden, like sleeping giants, in the multitude of poetic metaphors and verses of Vedic literature. He meant exactly what he said: the *Vedas* speak of the universe in terms of billions of years and trillions of miles, which no other ancient civilization did. This is remarkable on its own; yet there is much else to discuss.

What is called the Vedic Era stretches roughly from about 1900 B.C. to 300 B.C. Strong differences between this era and that of the Indus Valley civilization have been explained in various ways (e.g. invasion), with no final consensus. One major difference is that the Vedic Era saw wars, empire building, the erecting of fortresses, and other realities of widespread conflict. Yet, like the Harappan period, it also marked the advent of a magnificent intellectual culture, one that likely benefited from what went before.

Parts of this culture can be seen in the *Vedas* themselves and in the texts associated with them that came later. As originally created, these include a vast body of material that covers many topics dealing with religious practice, philosophy, and the origins of the cosmos and everything within it. Authorship of most works is unknown. Almost certainly there were many contributors – poet-priests and poet-sages who created verses in a form that could be memorized and passed on orally. For example, it is clear that astronomical understanding spans different periods of time. The *Vedas* themselves represent much older thought – when first written down in the last few centuries B.C., they were already windows into a distant past.

The four *Vedas* are compilations, or Samhitas, of hymns and chants. They are: the *Rig* (hymns recited by priests), *Yajur* (manual of sacrificial rites), *Sama* (chants sung by priests to music), and *Atharva* (spells, incantations, and metaphysical hymns). The *Rig Veda* is the oldest and is generally considered the most important of the *Vedas*, as the others draw from it abundantly. Each *Veda* came to have material added to it: the prose Brahmanas that provided discussion and also details for how religious ceremonies are to be performed; the *Aranyakas*, for rituals not performed in public; and the *Upanishads* ("Sittings near a Teacher"), which are philosophical commentaries that introduced the ideas of karma, reincarnation, and yoga. Finally the *Puranas* treat the whole of Vedic cosmogony (creation cycles, history of gods, story of humankind) and Hindu mythology up to about 1000 C.E. In addition to all these texts, there are others relating to more specific subjects that seem to represent re-writings and inspirations from material in the *Vedas*, such as the texts of Ayurveda medicine (discussed in the following). Analysis of the content and language of each *Veda* suggests that there is a declining progression in age of composition from about 1500 B.C. (*Rig Veda*) to 600 B.C. (*Atharva Veda*). Such is a very brief description of a vast and highly complex literature.

The language of the *Vedas* was Sanskrit, which acted as a powerful and highly fruitful *lingua franca* throughout South Asia for many centuries thereafter. Its capabilities were greatly enhanced by the standardizing work of Panini, who provided a highly sophisticated grammar, analysis of morphology, phonetics, and syntax – essentially a full-scale linguistics of the language – sometime between the 5th and 3rd century B.C. Even well before Panini, but certainly after him and thanks to some of his work, Sanskrit had the ability to easily combine nouns, or parts of nouns, and create new terms of much ingenuity. The vast number of names, titles, and terminologies in the *Vedas* are a direct result of this capability (and can easily become confusing to those unfamiliar with Vedic writings). In any case, Panini's work and the writing down of the *Vedas* marked a distinct boundary, essentially the end of the Vedic Era itself and the beginning of written science. Through its influence on Persian and Arabic, then Latin, a fair number of Sanskrit words, in derivations, have made their way into modern English, e.g. atoll, avatar, bandana, beryl, candy, cheetah, cot, guru, jackal, juggernaut, jungle, lilac, loot, nirvana, opal, pundit, sugar, shampoo, swastika, thug, and yoga, to mention a few.

According to information derived from the *Vedas* themselves, society in the early Vedic Era was pastoral, even semi-nomadic, but by the middle and later periods, came to be highly organized in all domains. Unlike the Harappan culture, Vedic people over time became stratified according to birth and ruled by a dynastic monarchy. In later Vedic time, from about 800 B.C., large kingdoms developed. This proved to stimulate the arts and sciences as well, as a number of major rulers and their courts acted as patrons of learning and artistic expression. There were distinct classes by this time, understood to represent specific organic parts of the cultural body: the *Brahmanas*, the scholarly class, represented the mouth according to Vedic literature; the *Kshatriyas* (aka *Rajanyas*), the ruling class, were the arms; the *Vaishyas*, the business/merchant class, probably the largest part of society, was its stomach; and the *Sudras*, the labor class, constituted the feet on which society stood.

Meanwhile, the *Vedas* also contain fundamental ideas about the nature of the physical world. These ideas merge the spiritual and material dimensions into an all-inclusive kind of system that is elaborated in complex ways by the different Vedic writings. For our purposes, a few big ideas are essential. One of these holds that the creation of the universe, including the Earth, Sun, Moon, planets, and stars, came from a universal and unseen force or power, not from the gods (or God). And yet there is a lack of certainty; no final knowledge exists about this force or from where it came. The *Rig Veda* makes this entirely clear in Book X (verses 5–7), where it takes up Creation:

> There were begetters, there were mighty forces, free action here and energy up above. Who verily knows and who can here declare it, whence it [universe] was born and whence comes this creation? The Gods are later than this world's production. Who knows then whence it first came into being? . . . Whose

> eye controls this world in highest heaven, He verily knows it, or perhaps He knows not.

The *Rig Veda* does not provide a teleological explanation of creation. Instead, we are given a statement suggesting the limits of human inquiry. It is tempting to draw parallels from this to the grand uncertainties of modern cosmology and astrophysics, for example to concepts like dark energy and dark matter that define "mysteries of the universe." Yet all such correlations take Hindu thought out of its original context and, therefore, run the risk of exploiting it for modern purposes. It is always advisable to be extremely cautious about constructing any such parallels, as well as the purpose for doing so. This being said, there are nonetheless ideas germinated in ancient scientific-religious cultures that have been passed down, rediscovered, and even reformulated in much later times.

Central to the fundamental Vedic view, for instance, is that everything in the universe is in a state of constant transformation. Change involves new arrangements, or manifestations, of eternal, indivisible particles or elements, which thus define a kind of atomism. These "atoms" take the form of the "five great elements," *panca-mahabhuta*, that make up all things, including the human body – water, earth, fire, air, and space (also translated as ether or sky).

Water forms the basis for life, both within living things (fluids in plants, animals) and externally, as rivers and lakes, rain and ocean. Fire is a source of warmth, light, creation and destruction, and is associated with the Sun, the origin of day and night, the seasons, growth. Earth gives solidity and is the basis for the growth and survival of plants, therefore foods, as well as the source for natural materials that humans utilize for building, protection, art, industries. Air is associated with the breath and breathing, thus life from moment to moment. Space, finally, is the element that links all the others together, providing a realm in which they exist and interact. These elements had a sequence of creation: "From Brahma's mind sprung space, from space air, from air fire, from fire water, and from water earth," as expressed in the *Surya Siddhanta*. Order in the universe depends on a natural, dynamic balance among the five elements in all their multitude of manifestations. This applies to the daily life of an individual as well as to the solar system. When balance is lacking, events like violent storms, floods, and earthquakes, as well as disease, injury, and death, occur.

A large number of religious rituals in the *Vedas* depended upon, and also embodied, specific types of scientific content. Examples include astronomical and mathematical understanding and many observations of the natural world, such as that quoted at the beginning of this chapter. Many technologies originated and evolved during Vedic times in response to commercial and military needs, as well as knowledge from other regions, notably Babylon/Assyria, with whom trade had been restored. Metallurgy after 800–900 B.C. now included iron as well as copper, bronze, and gold/silver; by the first centuries C.E. it had further expanded to include the world's first use of zinc. Iron metalwork was especially important, not only for weapons, but for tools able to clear the thick forests of the Ganges Plain and expand agricultural land, thus food availability. This, in turn, supported the rise of large urban centers. Regarding education, some indication is given by the *Upanishads* (*Ishavasya Upanishad*), which advise all who will be educated to study both the physical and spiritual sciences, the aim of human life being to seek an understanding of Brahman – body, mind, and spirit.

Many aspects of Vedic society, from its political organization and class system to its ceremonies and rituals, express a deep belief in an eternal order uniting all things. This order was not strictly religious but involved material objects as well as the workings of the human mind. Order was infinitely repeated at the grandest and most miniscule scales.

The end of the Vedic Era is associated with the rise of Buddhism in the early 5th century B.C. Over the next two centuries, western and northern India were subject to a series of invasions and conquests, first by the Persians and then Alexander the Great, who entered India in 327 B.C. Alexander's reign did not last long; it was replaced by the Maurya Empire (322–185 B.C.), then a period of splintered kingdoms, and finally the age of the Guptas, known today as the Classical Period. It was during this period, lasting from about 240 to 550 C.E., that stability and enlightened government returned. The sciences, mathematics, the arts, and learning in general all reached a remarkable height under the Guptas. With Sanskrit as its flexible medium, natural science found a "golden age" that would come to influence the greater known world.

Astronomy: *Vedas* to Aryabhata

The tradition of astronomy in early India is among the most advanced in the premodern world. Why is this so? One reason is the blending of celestial observation and mathematics at a very early stage, even before the creation of the *Rig Veda*. Another reason, particularly remarkable to those brought up in the western tradition, is that a great deal – even the majority – of early Indian astronomy was expressed in poetry. The rigors of poetic convention, including both rhyme and meter, added a dimension of ingenuity and discipline beyond what was otherwise needed for expression of scientific knowledge. The individual who looms largest in this long tradition went even well beyond this, using the resources of the Sanskrit language to create a poetic-mathematical "code" able to express in highly condensed form a considerable number of observations, measurements, and discoveries that subsequently impacted Islamic and, later, European astronomy. Indeed, the study of pre-modern science often reveals a need for us to take note of the forms in which knowledge occurred.

Vedic astronomy

Scholars have often stressed the importance of astronomy in particular for Vedic society. Such importance was definitely true for other early civilizations: the cyclic movements in the heavens and their seeming eternality posed the questions of humanity's place and meaning in the greater cosmos, the nature of time, and the laws that govern events. Vedic society answered these questions, in part, by the fundamental belief in the absolute unity of all terrestrial and cosmic reality. This unity ruled on every level of existence. It meant that a cosmos was present within each living thing, mirroring that of the universe itself.

Historians of science, led by understanding of astronomy's importance to Vedic culture, have recently begun to view the *Vedas* themselves as based on astronomical knowledge. Sometimes, this involves a symbolic retelling of such knowledge, for example in relations among the various gods or in the organization of the hymns and chants. While there is debate about the extent to which this may be true, scholars are in full agreement about one remarkable truth. Vedic astronomy is physically "written" into the design of altars built for religious practice.

The *Vedas* hold the universe to be infinite. They show the original authors had an understanding of the nature of eclipses, the difference between the lunar and solar years, and the need for adding extra days and months in order to make these agree.

The Moon's cycle was seen to be about 27 days, each day showing the lunar orb to be in a new asterism, or group of stars. These were used to define the 27 stations (later 28), or *nakshastras*, of the Vedic zodiac. These stations begin with the spring equinox and are central to Hindu astrology. Each has a presiding deity, e.g. station 1 is associated with *Agni* (god of fire); station 2 with *Prajapati* ("Lord of Creatures"); station 3 with *Soma* (god of the healing and uplifting drink, soma); and so forth. Children were named starting with the first letter of whatever *nakshastras* they were born under.

Another part of Hindu astrology involving the Moon has to do with the "shadow planets" Rahu and Ketu, which represent the north and south nodal points where the annual path of the Moon, as seen from the Earth, intersects that of the Sun (the ecliptic). These two ascending and descending nodal points are not fixed and move along the ecliptic plane of the Earth's motion. The rotational period of Rahu and Ketu is the same as that of the nodal points. These two shadow planets are actually the head and tale of a great demon, and when both the Sun and Moon arrive at one of these points (lunar nodes), they swallow one of these two celestial bodies, creating an eclipse. Thus were Hindu mythology and astronomical observation combined.

The *nakshastras* were also used in time-keeping and calendar-making. The particular alignments and positions of the *nakshastras* relative to the Sun correspond to dates between 2,300 and 3,000 B.C., suggesting an oral tradition in some manner inherited from Harappan times. The ability to use the appearance and position of stations to determine solstices and equinoxes shows that early Vedic astronomers/astrologers had instruments for measuring, tracking, and possibly mapping the planets and stars. These may well have been made of wood, since none remain. The Moon itself, we should note, was also known as *surya rasmi* – "the one that shines by sunlight." It would appear these early watchers of the skies understood that the lunar disk is lit by reflected light.

Vedic rituals, like those of many other peoples, were timed according to the new and full Moon, as well as the solstices and equinoxes, but it is in the construction of certain altars that fascinating astronomical and mathematical aspects reveal themselves. This is true, above all, for a set of sacrificial altars dedicated to the fire god

Agni, one of the supreme deities of the *Rig Veda* who links the Earth and human beings to the heavens and the gods. These fire altars, in fact, served as a nexus for the scientific intelligence of Vedic society. Their detailed structure, carefully planned and likely diagrammed beforehand, is like a visual language, expressing how the universe fits together. Precision of construction was required; otherwise, an altar would fail in its purpose. Instructions are given for three types of altars to be built together, representing earth, space, and sky. Each has a different shape – Earth is circular, space semi-circular, and sky a square – but they are required to have equal areas (the concept of oneness). This created the demand for geometric and algebraic solutions. Figure 4.3 shows one of these solutions, based on a procedure for producing a circle (Earth) with the same area as a given square (sky).

Scholars have interpreted the single, distinctly astronomical/astrological text, the *Vedanga Jyotisa*, as highly saturated with mathematical relationships. This work

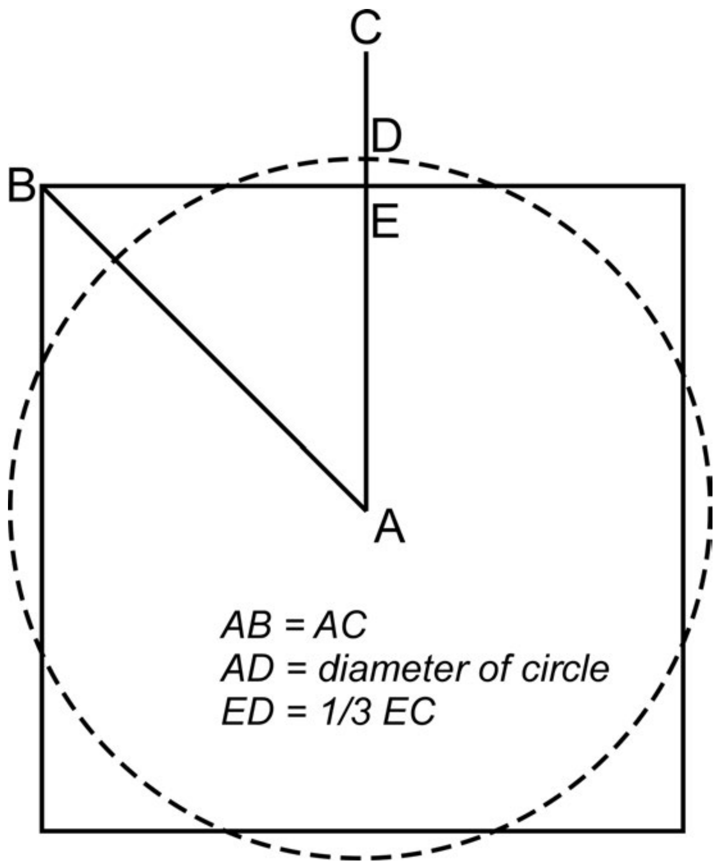

Figure 4.3 Turning a square into a circle of equal area, according to the *Baudhayana Sulba Sutra* (ca. 600 B.C.). The directions are summarized in the three lines in italics and discussed in the text.

was originally composed around 1370 B.C. (one accepted date for it), though not set down until a thousand years later. We know this from the position of the winter and summer solstices mentioned in the work. In written form, therefore, it represents knowledge that had culminated much earlier. Most of the preserved text is concerned with concise formulas for calculating the times of monthly and seasonal rites, including sacrifices. It deals with rules for observing the stars and planets, for lunar and solar months, and for making calendars. The *Vedanga Jyotisa* begins the year with the winter solstice (December 21) – an important new standard, using astronomical information from older traditions that relied more exclusively on religiously defined seasons.

Measurements of time are central. Indeed, the entire first portion of the text is devoted to definitions of time units and how they help measure celestial cycles. A simple example is this verse: "The Moon comes into contact with each asterism 60+7 times during the *yuga* [5 years]. The Sun stays in each asterism 13 days plus 5/9 day." The day, therefore, is a basic time unit and is itself divided into kalas, with 603 kalas in one day (roughly 25 kalas per hour). Why this seemingly arbitrary division? The answer comes from a relation between the solar year and the Moon's travel through the *nakshastras*. That is, there are counted 366 days in a solar year and thus 1,830 in the five-year interval of a *yuga*. Also within a *yuga*, the Moon was known to pass through 1,809 *nakshastras*. If we divide the number of solar days by the number of *nakshastras*, we should find how long it takes for the Moon to travel through one station: 1,830 ÷ 1,809 = 1.0116, which turns out to be 1 + 7/603. Another example? Here is a simple one: Vedic astronomers had correctly surmised that both the Moon and the Sun are approximately 108 times their respective diameters from the Earth. It is a curious coincidence that 108 is considered as a holy number among the Hindus and Hindu rosaries for prayers have 108 beads.

Much of the *Vedanga Jyotisa* consists of numerical formula to be memorized for finding positions of lunar and solar *nakshastras*, time intervals required for work, and also corrections for the length of days and years. In fact, the text knowingly gives simplified, slightly incorrect intervals – the *yuga* including five years of 366 days – so that the system is easier to remember. Nonetheless, numbers indeed, and relations between them, seemed to permeate and unite all aspects of the cosmos.

This brings us back to Carl Sagan's comment about the scale of Vedic time and distance. Though eternal, the cosmos of the *Vedas* undergoes cyclic creation and decay, its reality divided between a materialized and differentiated state and a latent, undifferentiated state. Times and distances vary between different texts; however a consistent example of cosmic scale is given in the *Puranas* regarding the creation, destruction, and recreation of the universe. This cycle is associated with a day in the life of Brahma, creator of the world. A new universe emerges when Brahma awakens and continues until he goes to sleep, after which it degenerates. This single day, known as a Brahma-kalpa (kalpa = "eon"), is equivalent to 4.32 billion years. Brahma himself lives for 100 kalpa years, which means: 4.32 billion × 360 (day/night cycles per kalpa-year) × 100 = 311.04 trillion years. The current period of human history occurs within the 51st year of Brahma's lifespan.

Sagan, therefore, was entirely correct. Today, we can only wonder at the imagination that created a mathematics of such scale. It seems nothing less than an attempt to speak directly about the divine, the measure of its realm, and, of course, about the origins and longevity of the heavens themselves.

The Hindu calendar

As outlined in Vedic literature, including the *Vedanga Jyotisa*, the Hindu calendar can be described as luni-solar. Similar calendars were created by the ancient Hebrews and Babylonians. Months are based on the Moon's movements, while the year is measured by the Sun's complete cycle through the asterisms (constellations), i.e. the Earth's orbit around the Sun.

A luni-solar calendar had the advantage of being based on observation of the two primary celestial bodies in human experience. In the Hindu version, the year began on the spring equinox (northern hemisphere), March 20 or 21, corresponding to the Sun's appearance in the constellation *Mesha* (Aries). Each month, meanwhile, was divided into two parts, associated with the waxing and waning of the Moon. From the New Moon to the Full Moon, as the lunar orb grew more full, Vedic culture assigned the name *Shukla paksha*, meaning "bright half." This period of about 15 days was viewed as auspicious; a great majority of religious festivals took place during this time. The waning period, from the Full Moon to the next New Moon, was the *Krishna paksha*, or "dark half," considered less fortunate, due to the weakening of the Moon's brightness (influence).

The complexities of celestial movements mean that some of these designations are general. For example, the Sun does not always transit so nicely from one asterism to another in accord with a lunar month. When a month passes and the Sun remains in the same constellation, then the upcoming months will need to be renamed or otherwise adjusted. As a result, observations of the heavens were always in progress.

Though observation was the basis for these designations, differences between the lunar and solar years require some kind of mathematical adjustment. Twelve lunar cycles encompass a mean of 354 days, while the mean solar year is 365 days long. This difference was accommodated by adding an extra month every 32.5 months

The 12 months of the Hindu calendar were divided into 6 *ritu*, or lunar seasons, partly for agricultural and partly for astrological reasons. Beginning with the start of the new year and including roughly two months apiece, these seasons were: Spring (March 20–mid May), Summer (late May–mid-July), Monsoon (late July–mid-September), Autumn (late September–mid-November), Winter (late November–mid-January), Cool Season (late January–March 19). As suggested by these names, seasons were also correlated with ecological events, such as the blooming and withering of plants, the habits of animals, and other natural signs.

These brief comments provide only the most general outline. A full accounting of the divisions of time included in the Hindu calendar would require many pages, beginning with the cosmic lifespan of Brahma (trillions of years) and ending with time segments of individual days, "hours," and "minutes" (Hindu divisions are different). One final aspect we might mention is that the most commonly used version of the calendar has a zero year and a first day. In modern terms, this is February 18, 3102 B.C., the day marking the start of the present era in cosmic history, known as the *Kali Yuga*. As of February 18, 2015, therefore, 5,117 years have passed in this era.

The siddhanta tradition

From roughly the end of the Vedic Era there rose a new tradition of astronomical knowledge and composition. The term "siddhanta" means something close to "established understanding" or "tradition" and in astronomy was used to designate a literature that provided a summary of existing knowledge. To this end, the Siddhanta were a series of handbooks or perhaps textbooks for learning and applying astronomical facts, formulas, and discourse (terminology and usage). While the siddhanta tradition seems to have originated before the beginning of the Christian era and to have included up to 18 well-known works, only five of these survived to the medieval period, the most influential being the *Surya Siddhanta*.

Dating from the 4th or 5th century C.E., the *Surya Siddhanta* contains much specific information regarding planetary and celestial dimensions, plus instructions for computing various positions, time durations, and other factors important for religious rites, including astrological predictions. Here can be found information on the divisions of time, prograde and retrograde motion of the planets, precession of the equinoxes, the nature and occurrence of eclipses and parallax, rising and setting of stars, and much more. There is much use of geometry in the multitude of formula given for the calculations discussed. Several chapters (e.g. Chapter 6, "On the Projection of Solar and Lunar Eclipses") give directions for drawing figures that illustrate the information being presented.

Three aspects to this siddhanta are striking. First, its time divisions extend from the extremely small to the inconceivably large, from the *truti* (29.63 microseconds) to the *maha kalpa* (3.1101×10^{14} years). Second, this text is the earliest known to contain a table representing solutions to the sine function. In their geometric analyses of celestial motions, Indian astronomers had discovered a method of calculation that suggests the sine/cosine functions, so accurate are the figures in the mentioned table. Such figures were highly useful in numerical calculations for finding the positions of bodies moving through a circular arc. Third, we find that the diameter of the Earth is given as "1,600 yojanas," which, if we accept the commonly-assigned distance of five miles for a yojana, equals 8,000 miles – a nice, neat number that is obviously simplified. Astronomers, that is, knew a more precise figure (this was very close to the actual figure of 7,918 miles).

Finally, the modern reader is likely to find remarkable this brief little paragraph:

> Thus everywhere on [the surface of] the terrestrial globe, people suppose their own place higher [than that of others]: yet this globe is in space where there is no above and below.

Aryabhata: a high point in pre-modern astronomy

The earliest Indian astronomer – and many historians believe the greatest – whose work has survived to the present is Aryabhata. He lived from 476 to 550 C.E., probably in northern India, during the waning years of the Gupta Empire, known as a "golden age" of the arts and sciences in early India. Though he apparently wrote several works, only one has survived, the *Aryabhatiya*, composed according to its author when he was only 23. It is considered a masterpiece of intellectual creativity, not only in the sophistication of its knowledge but, as we noted in the beginning of this chapter, in its form. The *Aryabhatiya* follows the tradition established by the *Vedas* in using poetry to express its science. But it does this in a highly creative fashion.

Aryabhata created a type of code in which all numbers, up to 10^{18}, could be represented by consonants and vowels of the Sanskrit alphabet. In simplified terms, consonants were assigned integers (1, 2, 3 . . . 25, 30, 40 . . . 100), with vowels given powers of ten. Thus, words become numerical values and, with proper cues (e.g. punctuation), they can be arranged into equations, tables, the values of particular phenomena, and more. The added layer of creativity in the *Aryabhatiya* is that all of this is done in the highly condensed and poetic form of verse couplets, with many words representing both their linguistic and numerical meanings. When we consider, finally, the complexity and diversity of astronomical knowledge expressed in this way – in a mere 118 verses, the author presents a summary of Indian mathematics and astronomy, along with a number of original conclusions – we can hardly fail to be impressed, if not amazed. In fact, systems of this kind may have existed before but were never so intricate. Why the author chose such a system is not known but may be surmised. Though the Vedic Era, when knowledge was passed orally, had long given way to a textual culture, the decline of the Gupta Empire promised to bring chaos and degeneration (which, in part, it did). We may guess that Aryabhata wanted to produce a work that could be memorized without great effort and that might thus survive the vicissitudes of an uncertain future.

The book is divided into four parts: an introduction (part of which explains the coding system); a mathematical section; a part on calculations involving time; and a final section on spherics (geometry and trigonometry of figures on a sphere). In the mathematics part, Aryabhata gives 66 rules and formula (without proofs), while also discussing how to solve equations in algebra and trigonometry. His solutions are not our modern ones but consist of what he calls *kutakka* (to pulverize), by which a problem is broken down into smaller and simpler sub-problems, whose solutions can then be combined. He also goes over methods for finding square and cube roots – the latter being a notable innovation. No less impressive, Aryabhata provides the most accurate estimate of π up to that time, 3.1416 and correctly labeled it an approximate value.

The second part on time computations deals mainly with planetary astronomy. Aryabhata also estimates the circumference of the Earth (at the equator) to within 95 miles of the modern number. He states: "Sunrise at [Sri] Lanka is sunset at

Siddhapura, midday at Yavakoti [Yamakoti, Indonesia], and midnight at Romaka [Rome]." This tells us the author was using a system of longitudes, probably on a globe, *and* that he must have had some idea about the speed of the Earth's rotation. Obviously, he did not know the simultaneity of sunrise in Sri Lanka and midnight in Rome by video conference call or satellite imagery. He could only have determined it using geometry informed by astronomical knowledge. That he also said that "[Sri] Lanka is 90 degrees from the centers of the land and water [i.e. the north and south poles] and Ujjain is straight north of Lanka by 22 ½ degrees" confirms he had a map or globe at his disposal.

Finally, in the last part of the book, the author uses trigonometric relationships to discuss celestial motion and eclipses. But what has struck historians of science no less than all of this are two conclusions the author makes, shown by these brief passages:

> Half of the spheres of the Earth, the planets, and the asterisms [stars] is darkened by their shadows, and half, being turned toward the Sun, is light . . . according to their size. . . .
>
> As a man in a boat going forward sees a stationary object moving backward, just so a [Sri] Lanka man sees the stationary asterisms [stars] moving backward in a straight line.

Aryabhata tells us in no uncertain terms that the Earth, Moon, planets (and stars) are spheres and all shine by reflected light. This is impressive, though not especially remarkable in the 5th–6th century C.E., given that the author was here repeating a fact that had been known for some time. The second passage, however, should grab our attention. It says that the movement of the heavens is caused not by any turning of a celestial sphere but instead by a rotating Earth. Such was an idea that stood directly against traditional thought, not only in India, but also in Greece and Babylon.

Assigning motion to the Earth opened a Pandora's box of criticisms and questions. Eight centuries before Aryabhata, Aristotle had argued strongly against the possibility of any motion for the Earth. Six centuries after, the Islamic scholar al-Biruni criticized the idea with the statement that "if that were the case, a bird would not return to its nest as soon as it had flown away from it towards the west." In a geocentric system, there is no need to assume axial rotation for the Earth as most observations, though wrong, are easier to explain. Once you define day and night due to Earth's motion, the explanation of other astronomical phenomena becomes complex. In a heliocentric system, axial rotation of the Earth becomes a necessity. Interestingly, in a geocentric system, the inner planets, Mercury and Venus, should have the same period as the Sun. Aryabhata does tell us this observation. However, soon after, in his text, he gives a different values for the periods of Mercury and Venus that are quite close to the accurate values. This has intrigued astronomers ever since. Some believe that Aryabhata's model was based on a heliocentric model and was later reduced to a geocentric to stay in tune with the existing practice of his time and to help ensure he would have followers. There is no way to tell, finally. What we can be certain of is that he took a major step in assigning axial motion to the Earth.

Indeed, belief in a stationary Earth ruled in the West for another thousand years, until Copernicus in the 16th century dismantled it, using a very similar argument to Aryabhata's.

The *Aryabhatiya* proved to be the most influential single work of pre-modern astronomy in India. Nearly every major mathematician and astronomer up until the 19th century wrote a commentary on it. Among the most important were those by his brilliant followers of the 6th and 7th centuries, Bhaskara and Brahmagupta. By the time these two thinkers were writing, the decimal system for whole numbers had been developed in India, which Aryabhata did not know – thus, we can say this system must have evolved in the brief period between about 550 and 620, when Bhaskara finished his commentary on the *Aryaghatiya*. This, indeed, was a momentous time for numbers, since Bhaskara is also identified as the first, or among the very first, to employ the zero, to which he assigned an open circle as its symbol.

Mathematics

Though we have covered some material of early Indian mathematics, there remain crucial facts to note and discuss. In general terms, it seems beyond question that Vedic society, or the religious-intellectual dimension to it, developed an idea of the world that Galileo would give voice to many centuries later: "Mathematics is the language in which God wrote the universe."

No doubt the most crucial fact, one that is far too often overlooked or unknown in its importance, is that like Newton and Descartes, we are all Indian mathematicians today. This is because the numeral system we use and the place-value decimal scheme with which we use numerals – allowing every possible number to be written with a mere ten symbols – comes from ancient India. So does the zero, as already mentioned. As for place notation, this we have seen, in rudimentary form, at Babylon, which employed a sexagesimal (base-60) scheme. Invention of base 10 has been attributed both to India and to China; its origins remain obscure. Yet its transfer to Islam and then to Europe clearly began with Arabic translations of Indian sources. The phrase "Arabic numerals" is, therefore, a misrepresentation; indeed Islamic scholars knew them as "Hindu numerals." Their final forms, as we know them today, did not exist until the 15th century. The Indian forms themselves, known as "Nagari" (Figure 4.4), were adopted into Islamic mathematics in the 11th century. These were translated along with Arabic texts into Latin starting in the 12th and 13th centuries, and they found something close to their final appearance when they needed to be standardized in Europe, due to the invention of printing. Thus, it is perhaps more accurate to say we are all Indo-Arabic mathematicians now.

A number system is an invention, a form of technology. It can give us the ability to record, analyze, define, and, ultimately, order and control a major part of

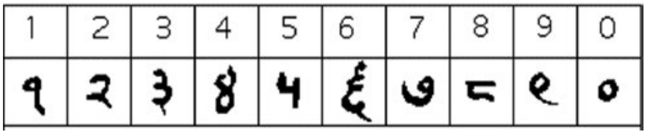

Figure 4.4 Nagari numerals, ca. 11th century C.E.

our activities and environment. We have seen how this was achieved in Egypt and Mesopotamia, how critical the use of numbers was to both these civilizations. The ten numeral, base-10 scheme has proven far more powerful over time than any other system ever invented. Modern science and technology would not be the same without it.

Well before this scheme was invented, Indian mathematics were already at a very high level, as expressed in the *Sulba Sutras*. These represent late Vedic writings, part of the Vedanga appended to each of the *Vedas*. Based on their language and grammar, the *Sulba Sutras* date from 800–200 B.C. The oldest of them, from 800–600 B.C., but composed earlier than this, is known as the *Baudhayana Sulba Sutra*, as its authorship is attributed to a man of that name. The purpose of these sutras was to provide detailed instructions for the performance of sacrifices and for the precise building of the fire altars discussed previously. Such construction involved directions and even implicit forms of proof directly related to the geometry of circles, squares, rectangles, and trapeziums of specific dimensions. As such, it could be said that these documents comprise something approaching an early geometry "textbook."

Several aspects are especially significant to the modern eye. There are procedures given for changing a rectangle into a square of equal area, a square into a circle, and a circle into a square, as well as for constructing a square twice the area of a given square. There is also a clear version of the Pythagorean theorem, along with triplets (calculated lengths of the three sides of right triangles). Vedic mathematicians were able to determine square roots, including those that produce irrational numbers, to a moderate-high degree of accuracy.

Let us take the procedure for transforming a square into a circle of the same area (see Figure 4.3). The *Baudhayana Sulba Sutra* gives us these directions: "Draw half [the square's] diagonal from the center towards the north-south or east-west line; then describe a circle together with a third part of that which lies outside the square." Figure 4.3 offers a diagram to demonstrate how these directions were followed. We see half the diagonal of the square, line AB, drawn toward the north as line AC. Next, a third of the length of EC protruding beyond the square is marked off at point D and used as the radius of the circle, whose area comes close to that of the square. A similar kind of rule is given for transforming a circle into a square. In this case, the method involves dividing the circle's diameter into 15 parts and using 13 as the side of the square. Obviously, these procedures are not exact; the formula provides an approximation. But for the building of altars, it was no doubt good enough from the viewpoint of human perception.

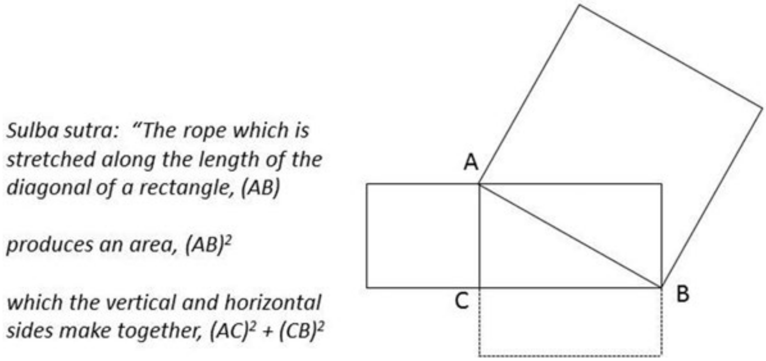

Figure 4.5 Directions given in the *Sulba Sutras* for the Pythagorean theorem.

For the Pythagorean theorem (Figure 4.5), as mentioned in the *Baudhayana Sulba Sutra*, we first recall that, in modern terms, this is expressed as $a^2 + b^2 = c^2$, with a and b as the two perpendicular sides of a right triangle, and c as the hypotenuse. It is unlikely that Pythagoras himself ever articulated the theorem this way; in fact, we have no text within 900 years of his life that tells us how he did formulate it. We do know that Euclid's *Elements* provided a proof of it using axioms and a step-wise procedure. In the *Sulba Sutras*, no such extended proof is given. Rather, instructions are provided in terms of measuring out a distance, since the goal is building an actual structure (an altar). Thus, we read (in approximate translation): "The rope stretched along the length of the diagonal [of a square] produces an area which the vertical and horizontal sides make together." Referring to Figure 4.5, this statement tells us that the area of the square with side c is equal to the sum of the areas of squares a and b, which is simply another way of stating the theory as we know it, since the area of each square is a^2, b^2, and c^2. This form of the theorem overlaps that of Euclid, whose proof is for a rectangle, not a square, and, therefore, much more elaborate and sophisticated.

For finding square roots, this type of measurement-based procedure is also used. It may have come from the need to generate a square twice the area of a starting square (e.g. scaling up the size of a square altar). To understand it, we might recall that by the Pythagorean theorem, if our starting square has a side of 1, the hypotenuse will be the square root of $1^2 + 1^2$, thus $\sqrt{2}$. Summarizing the procedure given by the *Sulba Sutras*: "Increase the side of the original square by a third, and this third by its own fourth less the thirty-fourth part of that fourth. This will be the side of the new square." That is:

$$1 + 1/3 + 1/3 \times 4 + 1/3 \times 4 \times 34, \text{ which} = 1.4142156\ldots$$

The actual value of $\sqrt{2}$ is 1.414213, so we can say the above is accurate to five decimal places.

No evidence of how this rule was obtained, nor the similar rules for changing squares into circles and vice versa, is ever mentioned. Scholars have come up with a number of ingenious ways by which such proportions were derived. Yet these rules might also strike us today as something generalized from "experiment" or, rather, experience – using bricks to physically lay out the desired transformations and then measuring the dimensions (doing this even repeatedly), rather than deriving them mathematically. We have seen the same type of rules, after all, in Egyptian and Mesopotamian mathematics. Such is not to belittle the achievement; on the contrary it deserves special discussion, given in the final section of this chapter.

Following the Vedic Era, two traditions of mathematics developed in India. One of these, involving the siddhanta texts, we have mentioned. Their signal importance, from the point of view of later mathematical thought, was their publication of the first sine tables (though not designated as such) in the *Surya Siddhanta* (4th c. C.E.). This was subsequently developed further by Aryabhata and Brahmgupta and then, in the 8th century, transferred to Arab mathematics. Aryabhata's tables were for true sine functions, giving the length of half chords, which he called *jya* and which Arabic translators adopted as *jiba* or, in some versions, *jyb* (the *Aryabhatiya* was translated several times). In the 12th century this Arabic rendering was mistaken by Latin translators, who went looking for an indigenous Arabic word, such as *jaib*, meaning "fold" (of clothing) or "opening." It thus became *sinus* and from there *sine* by the 16th century. What we use today, therefore, is a misreading of a transliteration from Aryabhata.

While there is a great deal more about the early history of Indian mathematics to cover, a most substantive topic requires our attention above others: the invention of zero.

As mentioned in the previous chapter, Sumerian and Babylonian mathematicians had a preliminary idea of this essential concept and used a type of place holder, a gap or two small marks, to represent it. But this was very different from inventing a new number that actually meant something – in this case "nothing" or "absence." The Greeks, meanwhile, had no such concept and neither did the Chinese. Its absence would have eventually limited the mathematics of these societies considerably, despite their many advances.

In one way, it makes sense that this innovation took place in India. The fundamental concept of void, as an essential element of the cosmos, was integral to Hindu, Buddhist, and Jainist philosophies from an early period. Moreover, the idea of "void" did not carry the meaning of total absence but rather of latency, a preliminary state of manifest form. We can imagine, too, that a separate numeral for zero was well-matched to a place-value, base-10 system, being able to magnify any number ten times when placed next to it. So zero had to be both a true idea and an actual number. Both of these factors came together sometime between the work of Aryabhata and Brahmagupta, as we have said, which means the late 6th century C.E. We know that Brahmagupta, in his work *Brahmsphuta-siddhanta*, formalized the concept thoroughly and influentially, though he probably adopted it from other works. His book, however, was key: not only did it assign a symbol to the idea but gave it a name (*sunya,* meaning empty) and described arithmetic rules for operations involving it with both positive and negative numbers, for example:

$$z + 0 = z \qquad 0 \times z = 0$$

$$z - 0 = z \qquad 0 / z = 0$$

$$0 + 0 = 0$$

$$0 - 0 = 0$$

How, then, did "zero" get its name? As is so often the case, translation proved the key originating process. Islamic scholars who translated the *Brahmsphuta-siddhanta* rendered the term *sunya* (empty) into its Arabic equivalent, *sifr*. This was then adopted phonetically into Latin as *cipher* and *zephirum*, which became *zefiro* in medieval Italian and eventually "zéro" in French.

The Iron Pillar of Delhi

Of all metals worked by early civilizations, iron was the strongest and the most corrodible. Water and oxygen are its two great enemies. Swords, armor, nails, or beams buried in shallow, wet soil or exposed to the weather fall before the power of rust.

How is it then that a 6.5-ton pillar of iron, standing 7 m tall in the outside air, has remained wholly intact for 1,600 years in Delhi, India? The Iron Pillar of Delhi (Figure 4.6) has attracted notice from metallurgists all over the world. Exposed to the weather in every season, dented as well, it reveals almost no sign of corrosion. Its inscribed dedication in honor of Candragupta II (reigned ca. 380–415 C.E.) is perfectly legible (Figure 4.7). The wording – "He [Candragupta], as if wearied, has abandoned this world and resorted in his true form to the other world" – suggests the pillar is a memorial.

At some point after its making, the pillar was moved hundreds of kilometers from an original site in central India for unknown reasons. In the early 18th century, Nader Shah of Persia, as part of his campaign to conquer the Mughal Empire, pillaged the city of Delhi, firing a canon ball to break the famed Iron Pillar in two. He failed. Indeed, this became an omen; Nader Shah was soon assassinated.

To answer the riddle of the pillar we need to know two things: how the iron was made and how rust forms. Nearly all iron ore mined in ancient times was either the red-brown mineral hematite (Fe_2O_3) or dark green-black magnetite (Fe_3O_4). Such ore had trace amounts of other elements, like silicon, magnesium, phosphorus, and sulfur. Smelting uses heat to drive off oxygen and concentrate the Fe. This was achieved in special furnaces using charcoal as fuel and a bellows to pump in air, producing temperatures of up

Figure 4.6 The Iron Pillar of Delhi. The pillar has stood for 1,600 years in the open without suffering from rust or corrosion.

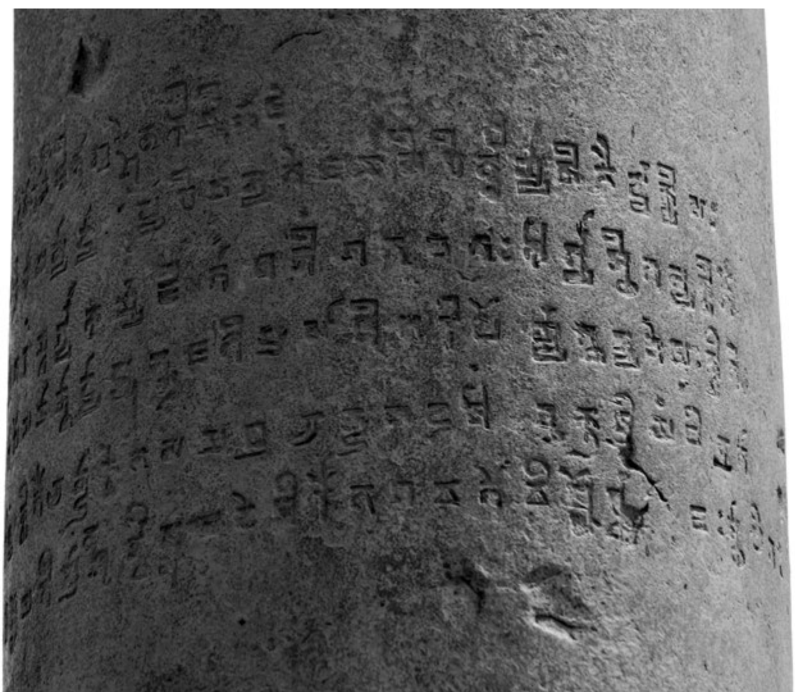

Figure 4.7 An inscription and chipped metal on the Iron Pillar of Delhi.

to 1,200°C. Smelting creates a spongy mass called "bloom" containing iron and partly melted waste called "slag." Blacksmiths hammer bloom to force out the slag and compress the metal, yielding wrought iron. This metal in ancient times was never pure; its properties could be affected by the impurities that remained.

Rusting, in simply terms, involves chemically reversing the process of forging – oxidizing the iron. It begins with moisture on the metal surface, which dissolves oxygen and produces reactive OH^- ions. These draw iron (Fe^{+2}) from the metal, producing iron oxides ($Fe_x(OH)_x$), which precipitate out onto the surface. With a little time, the oxides change into a crumbly form of hematite. Scaly and porous, rust allows water and oxygen access to freshly exposed iron. The object is transformed into its own debris.

So what is the "secret" to the Iron Pillar? Perhaps we can guess: the answer lies in "unwanted" impurities. Modern analyses leave little doubt about this. Composition of the iron (by weight %) is unique: 99.4% pure iron, attesting to the smelting skill of its makers; 0.005% sulfur, 0.02% nitrogen, 0.03% copper, 0.05% silicon, 0.05% manganese, 0.05% nickel, 0.15% carbon, and 0.25% phosphorus. Noticeable is the large amount of phosphorus (P). Chemical analyses of other iron from central and northern India shows relative enrichment in P, indicating that this was in the original ore. Here is the key: this P forms phosphoric acid in water and when in contact with the metal surface, it prevents iron ions from reacting with OH^-. Instead, if the pillar is alternately wetted and then dried, the acid reacts with the metal to form iron phosphate – $Fe_3(PO_4)$. This precipitates on the surface as an insoluble coating that will not allow water to reach the iron. But we are left with a final question. Why doesn't modern steelmaking use phosphorus to finish its metals?

Medicine: Ayurveda

Sa'id al-Andalusi, an Islamic philosopher from 11th century Spain, in his famous book about the wisdom of the nations, had this to say about India: "they have surpassed all the other peoples in their knowledge of medical science and the strength of various drugs, the characteristics of compounds, and the peculiarities [diversity] of substances." Once informed about Vedic medicine, as practiced more than a thousand years before these words were written, we are unlikely to disagree with them in any way.

Al-Andalusi had not been to India. He spoke of its medicine as if it were like that of the Greeks and other peoples he knew more closely – reliant above all on drugs and substances. But medicine in al-Hind though it did utilize such things, was something quite different.

In Sanskrit, the word *Ayurveda* is composed of *ayur*, meaning life, and *veda*, which we already know, meaning knowledge. This gives a fairly accurate idea, in

English, of what Ayurveda is: an entire system of knowledge focused on human life, on keeping this life in a healthy state, and returning it to such a state when needed.

By "system," we mean that it includes both a coherent theory of human wellness and a set of practices to diagnose, treat, and prevent problems when they occur. This was somewhat true for ancient Egypt and Mesopotamia also. But in these civilizations, some part was always left to prayers and incantations, to the gods in other words, for healing and final determinations. Ayurveda begins from a different foundation. Its two most fundamental texts, the *Charaka Samhita* and *Sushruta Samhita*, written down like all the *Vedas* in poetic form, are far more extensive, coherent, and comprehensive. Particularly the *Charaka* discusses both medical practices and the logic and theory behind them.

Put into textual form sometime between 400 B.C. and 200 B.C., Ayurveda continues to be one of the world's most widely used medical systems today, practiced by nearly two billion people in India, Pakistan, Bangladesh, Sri Lanka, Nepal, Burma and by growing numbers in Europe and North America. Indeed, portions of Ayurvedic medicine involving therapies related to diet, natural medicines, massage, physical therapy, meditation, and more have become increasingly accepted both among the public and the medical community worldwide.

The two mentioned texts contain more than 10,000 verses and cover different but overlapping material. The *Sushruta* takes up the theory and practice of internal medicine, urology, skin and genital disease, oral diseases and dentistry, anatomy, surgery, treatment of animal and insect bites, and the name and preparation of various medicines. It is the more scientific of the two texts, in modern terms, as it defines actual medical diagnosis and treatment procedures in considerable detail. On the other hand, the *Charaka* presents definitions, basic principles of Ayurveda, reasons for becoming ill, approaches to treatment, advice and guidelines on healthful living, discussion of foods and their good and bad points, obstetrics, categories of herbal drugs, the physician's tasks and training, medical ethics, and related subjects.

Charaka notes there are three types of therapy: "spiritual, rational, and psychological." The first of these consists of "recitation of mantras, wearing roots and gems, auspicious acts, offerings [to deities] . . . atonement, fasting, invoking blessings," etc. Rational therapy includes "rational administration of diet and drugs." The psychological approach "is restraint of mind from unwholesome objects." One or more of these approaches may be appropriate to a particular patient. Meanwhile, the *Charaka* has some interesting advice for aspiring physicians:

> A doctor should drink snake's poison or hot iron instead of asking for money from a patient. In other words, a doctor must not take money from a patient even for saving his life. . . . This is the reason that a person who wants to become a doctor must make arrangements for his basic needs. He should be able to accumulate medicines and herbs so that he serves society and saves people's lives.

Charaka concludes, "He who practices not for money nor for caprice but out of compassion for living beings is the best among all doctors." Though doctors were advised to concentrate only on the treatment, the patient was advised to reward the doctor with money that he/she could afford and offer respect to the doctor. There is also discussion about the evils of quackery. The false physician "cures by chance," "promotes disease," and "kills hundreds." He is allowed to travel from place to place, demanding his fees, due to a lack of government oversight.

In providing the design of a hospital, *Charaka* suggests that the hospital rooms where patients stay should have good air ventilation and their size should be big enough for patients to walk comfortably. The rooms should also be protected from intense glare of sunlight, from rain, smoke, and dust as well. The patient should not experience any unpleasant sound, touch, view, taste, or smell. Expert chefs, servants, masseuses, nurses, pharmacists, and doctors should be hired to take care of the patients. Hospitals should serve quality food, should have enough drugs in the storage room, and a garden with medicinal herbs. Birds, deer, cows and other animals, along with singers and musicians, should be kept in the hospital compound.

What is the theory underlying Ayurveda? Though complicated and extensive, involving many specialist terms, a summary of some of its basic principles can be offered. This begins with the concept that all things in the universe are connected and that human beings contain elements and forces that exist in the cosmos generally. Health and disease come from interconnectedness between the mind, body, and the larger world. More specifically, they are directly related to the interactions the mind and body have with the external world – namely, activities, habits, diet, physical exercise, work, and people (friendships, love life, mentors, enemies, etc.). In modern terms, this would include "the whole person." Another key concept is balance: disease happens when some aspect(s) of the person are out of harmony with the universe of his/her life, when disruptions happen in the physical, emotional, or spiritual domains (or a combination). Every person is unique. Their constitution, or *prakriti*, defines a singular unity of bodily and psychological features that are part of that person for life and that impacts the tendency toward balance (health) and imbalance (illness, disease).

Most important among these features of *prakriti* are three dynamic life forces or energies, known as *doshas*, and their specific combination in an individual. As explained in the *Charaka*, each *dosha* is comprised of two of the five elements discussed above (water, fire, earth, air, and space), as well as other qualities, such as cold, viscous, slimy, sour, acrid. Each *dosha* has its own link to bodily functions and psychological characteristics. An imbalance commonly results from a situation that increases one or more aspects of a *dosha* beyond an equilibrium state. A person has all three *doshas* – they are present in every cell, tissue, organ, and fluid – but his or her *prakriti* is dominated by only one of them.

The Sushruta: *discussion and examples*

How are these brought together, intellectually speaking? As noted, the *Sushruta* and *Charaka* are long poems, and like all of the Vedic literature, were committed first to memory and passed down orally long before being written down. They are fascinating texts to read, for they are in the form of spoken lessons given to humanity by the gods, each text beginning with the story of a famous religious ascetic asking for knowledge that might help those on Earth who lead virtuous lives but still suffer from diseases. Many chapters continue in the god's voice but with much concrete detail about a particular illness, whether heart disease or hemorrhoids. An introductory chapter in the *Sushruta* begins like this: "Having clasped the feet of the holy Dhanvantari, who had arisen out of the primordial ocean . . . and who was the foremost of all knowers of truth, Sushruta interrogated him as follows: 'Tell me, O thou, the foremost of discoursers, all about the different locations and functions of the bodily *Váyu* (nerve force), both in its normal and agitated conditions. Instruct me. . . .'" The Dhanvantari answers this way:

> This vital Vayu, which courses through the body, is self-begotten in its origin, and is regarded as identical with the divine energy of eternal life, inasmuch as it is unconditional and absolute in its actions and effects . . . (like the sky and the atoms). . . . It is the primary factor, which determines the principle of cause and effect in all forms of created things. . . . It determines the growth, origin and disintegration of all animated organisms. . . . It has its primary field of action in the intestinal tract and the rectum. In its deranged state, it is the principal factor, which lies at the root of all diseases. . . . The Vayu in its normal or undisturbed condition, maintains a state of equilibrium between the different Doshas and the root principles of the body; it further tends to maintain uniform state in the metabolism of the body. . . .

Thus, listening to the god, we make a dizzying journey from the divine to the rectum. But, in fact, these are merely different aspects of a single reality that brings together fundamentals of energy, mind, and matter, including the *doshas*. Here, then, is evidence of a theory about the body and medicine, one that begins with the perception of an animating force or energy present in all living things. In the human body, specifically, the *vayu* begins with digestion, thus what we eat and otherwise ingest, and seeks forms of equilibrium among many processes and basic phenomena.

What comes next in the *Sushruta* is a catalogue of diseases, describing pathology, symptoms, and prognosis. Each disease entry will typically include a detailed description of symptoms, e.g. for kidney stones:

> A sort of excruciating pain is experienced either about the umbilicus, or in the bladder, or at the median of the perineum, or about the penis, during urination. . . . The urine is stopped at intervals in its outflow, or becomes charged with blood, or flows out twisted and scattered like spray. . . .

These verses are followed by an explanation: "Stone or gravel, originated through the action of the deranged *kapha* [*dosha*] saturated with an excessive quantity of that *dosha* by the constant ingestion of phlegm-generating substances. . . ."

There is a movement, in other words, from the empirical to the theoretical, with symptoms given in a highly concrete, precisely observed manner.

For treatment of kidney stones, several herbal medicines were given by the *Sushruta* and *Charaka*. One of these, proven fairly effective by modern pharmacological study, was *varuna* (Sanskrit), the small tree *Crateva magna*, which flourished naturally along creeks and streams all over India but, due to its medicinal uses, was also widely cultivated. For kidney stone therapy, bark from the tree was wetted, mashed, then mixed with water and boiled down to produce a decoction that could be taken by itself, with honey, in a small dose of about 50–100 ml (milliliters), or else mixed with a diuretic, such as carrot root. Clinical studies have shown that the drug helps break up stones and, if taken regularly, reduces their formation. It also has anti-inflammatory and antiseptic properties. As for prevention, the texts advise exercise (a less sedentary lifestyle) and less intake of beer and salty foods. These are among the recommendations also given today to prevent or reduce kidney stones.

Treatment and prevention are thus integral to Ayurvedic medicine. The primary goal is to restore harmony of mind and physical body through reestablishing forms of natural equilibrium. Illness represents a condition that needs to be removed in order that a person can find the most healthful way of living long term. This often begins, for a truly ill person, with a cleansing vapor in the sick room, using such plants as white mustard, as well as aromatic leaves or extracted oils from neem trees and hardened resins of shala (sal) trees.

The object of any specific treatment is to lessen states of imbalance or actual disease. Such treatments are very diverse. They may include herbal medicines, minerals (e.g. sulfur, copper, gold), various oils and tars (to stop bleeding and advance healing), forms of massage and physical activity, and also lifestyle changes dealing with diet, hygiene, skin care, periodic fasting or cleansing of the digestive system, and more. The *Sushruta* and *Charaka* also advise the physician to take care and not over-medicate a patient and, especially, to not administer too much of any single drug, as this will often result in poisoning.

The *Sushruta* also contains much discussion of surgery and related techniques, including dental surgery. Some procedures here are especially likely to impress or even amaze us today. One section, for example, covers cataract surgery, which uses a specially curved iron needle to remove the obstructing buildup of protein from the center of the lens. Another procedure involves repairing a damaged nose or earlobe with a skin graft, the graft coming from the patient's neck. More generally, the text states that any areas where tissue, bone, or tooth are removed must be either "purified" by the use of alkali or else cauterized with high heat. For dental surgery, specialized gargles or pastes are prescribed, made from herbal oils, ghee (clarified butter), and sometimes honey, which together reduce inflammation and pain and help prevent infection. One of the most fascinating procedures, however, involves treating an intestinal blockage ("Treatment of Parisrávi-Udara"):

> . . . the patient should be first treated with emulsive measures and fomentations [warm, moist applications, using clarified butter cooked with specific

> herbs, to reduce pain] and then anointed with sneha [cleansing herbal oil]. Then an incision should be made on the left side of the abdomen below the umbilicus and four fingers to the left of the line of hair which stretches downward from the navel. The intestine to the length of four fingers should be gently drawn out [and severed]; any stone, any dry hardened substance, or any hair . . . should be carefully examined and removed. . . . The two ends of the severed intestine should be firmly pressed and adhered together, and large black ants should be applied to these spots to grip them fastly with their mandibles. Then the bodies of the ants having their heads firmly adhering to the spots, as directed, should be severed and the intestine should be [moistened with honey and ghee and then] gently reintroduced into its original position and [the incision] sutured up.

The procedure ends with the surgeon bandaging up the wound and removing the patient to a "chamber protected from the wind," which we might understand as preventing exposure to external bacteria. Finally, "the patient should be made to sit in a vessel full of oil or ghee and his diet should consist only of milk."

In ancient India, the nose or earlobes were cut off as a punishment for some crimes, such as adultery. It was a lifetime embarrassment for the culprit. To avoid the embarrassment, rhinoplasty, the so-called plastic surgery, came to be widely practiced. In this process, flesh from thigh, cheek, abdomen, or the forehead was cut and new artificial parts were made. *Sushruta* provides the following process:

> The portion of the nose to be covered should be measured with a leaf. A piece of skin of the required size should then be dissected from the cheek, and turned back to cover the nose. The part of the nose to which this skin is to be attached or joined, should be made raw, and the physician should join the two parts quickly but evenly and calmly, and keep the skin properly elevated by inserting two tubes in the position of nostrils, so that the new nose may look normal. When the skin has been properly adjusted a powder composed of licorice, red sandal-wood, and extract of barberry should be sprinkled on the part. It should be covered with cotton, and white sesame oil should be constantly applied. The patient should take some clarified butter. When the skin has united and granulated, if the nose is too short or too long, the middle of the flap should be divided and an endeavor made to enlarge or shorten it.

Ayurveda, as practiced in ancient times up to the present, also prescribed forms of meditation and exercise, including yoga. The origins of yoga appear to be as early as the 4th millennium B.C.; clay figurines found at Mehrgarh show poses that closely resemble a number of those basic to yoga practice. Cylindrical seals dating from the 3rd millennium B.C. also depict figures in both seated and standing poses that show such resemblance. Traditional yoga practice defines a separate discipline from medicine per se, though it also overlapped Ayurvedic practices. It has the goal of combining exercise, breathing, and meditation (physical, mental, and spiritual dimensions) towards a state of peacefulness and self-enlightenment. This goal is first discussed in the *Katha Upanishad* (ca. 3rd century B.C.).

Yoga and Ayurveda both suggest essential connections between the Indus Valley and Vedic cultures. Some scholars consider such a link speculative, largely because any direct textual evidence is lacking. Such is one more reason why decoding the Indus script would be a tremendous advance in our understanding of ancient culture in this region.

Meanwhile, with time, modern medicine has come to accept many aspects of Ayurveda, particularly those dealing with diet, physical activity, use of oils and salves, relaxation methods, and the central importance of mind – the emotional psychology of illness, recovery, and wellness. In many ways, admitting the profound connection between our physical and emotional states is a major advance for healing and for common experience. It has opened new fields of research for modern medicine and expanded our own awareness. Today, the mind-body link is fully accepted worldwide and has been confirmed to play a role in many illnesses. In India, there are many university programs of Ayurveda medicine and a large number of doctors practice it alongside or blended with western medical practices.

Science and poetry

In western culture, it is called the "two cultures" problem. The sciences and the humanities, like two immiscible liquids, do not mix well. They give favor to different kinds of truth and do not always respect each other. So the story goes.

It is a story, however, that can seem strange to those raised in the Indian tradition. No such divide has ever existed here, where the *Vedas*, *Sushruta*, Aryabhata's work, and much else were all composed as poems. Writing certainly existed, particularly after 500 B.C., but the highest knowledge had been *spoken* to humankind by Brahma as poetry and was *shruti* ("what is heard"). So its transmission remained in this form for millennia. In his 7th century C.E., travels to India, the Buddhist scholar Yijing (also known as I-tsing) wrote of teachers who could recite hundreds of thousands of verses from the *Vedas*.

Human memory is greatly strengthened by the rhymes and rhythms of poetic language, a truth confirmed by much research. What seems remarkable about ancient Indian society is that even its most sophisticated texts, including the sciences, continued to be in verse. Al-Biruni, an 11th century Islamic scholar who lived in India for some 13 years, provides us with some interesting testimony:

> By composing their books in meters they intend to facilitate their being learned by heart, and to prevent people in all questions of science ever

> recurring to a written text, save in case of bare necessity. For they think that the mind of man sympathizes with everything in which there is symmetry and order, and has an aversion to everything in which there is no order.

Through the classical period (400–1100 C.E.), priests and scholars of Hindu background continued the oral-poetic tradition. They did so, moreover, even as they added to the corpus of written works. Scientists like Aryabhata had a foot in both worlds: they wrote works in poetic form amenable to being memorized in traditional fashion. And their students and followers seem to have done exactly that.

But aren't books the true protectors of thought? Gather them into a great library, and the best minds are safely at our disposal. Yet what is a library? A city of knowledge. Cities and books are both destroyed by fire, floods, invasion, neglect, decay. Among the greatest tragedies of the ancient world are the destructions of great libraries, like that at Alexandria. But while the textual ashes from the works of Ptolemy, Eratosthenes, Euclid, and Hipparchus darkened the Alexandrian sky, Vedic literature was being passed on by spoken words. Libraries in India suffered the fate of destruction too; indeed, during Islamic conquests they were burnt several times. Yet each time, they were revived.

How safe are our libraries of today? We might wonder. So much of contemporary science is in digital form. What elements of modern society does it depend on?

Nalanda: international university of the ancient world

In 427 C.E., one of the world's first great universities was founded at Nalanda, in the state of Bihar, north India. Even judged by today's standards, Nalanda was a marvel of educational vision. Dedicated mainly to Buddhist studies at first, it expanded into a training center for many areas of knowledge. At its height in the 7th century, it housed nearly 2,000 professors and as many as 10,000 students, who arrived not only from all parts of India but from China, Tibet, Indonesia, Japan, Korea, Persia, and Turkey. Its grounds were impressive to say the least: eight separate groups of buildings; ten temples; 11 monasteries; hundreds of classrooms and meditation halls; a nine-story library and scriptorium (where manuscripts were copied), plus expansive gardens and walkways, as well as lakes and parks.

The building of this great center of higher education was another mark of the "golden age" represented by the Gupta Era. While detailed records are lacking, it is apparent that the curriculum was wide-ranging. In addition to the Buddhist scriptures, students were able to pursue fields of science, especially astronomy, mathematics, medicine, and logic; the *Vedas*; yoga; schools of Hindu philosophy, and also branches of foreign philosophy. A rigorous oral exam was required for entry. No degree was granted, and there was no specified term of study. Research, in the modern sense, was not done; the university was a place of knowledge preservation and transfer.

Who were the students and professors? The majority were Buddhist monks and devotees. Like the student body, the faculty were from many parts of India but some also came from different nations. For example, famous Chinese scholars and translators of Buddhist texts, like Xuanzang (7th c. C.E.; also known as Hiuen Tsang), are known to have taught at Nalanda. The university seems to have gained considerable international status, and not only for students, since foreign rulers provided funds to help expand the campus at certain stages in its history.

Nalanda, it turns out, was not the only institution of its kind. Other centers of international learning in Bihar state included Vikramshila and Odantapuri universities, both founded in the 8th century, and the much older Takshila (ca. 600 B.C.–550 C.E.), where Panini taught. In addition to these were a number of other institutions of learning in different states: Valabhi (6th–12th c.), Gujarat state; Pushpagiri (3rd–11th c.) in the ancient kingdom of Kalinga; Somapura university (8th–12th c.) in Bengal; among others. In short, by the 700s, India had become a center of learning known from the Mediterranean to the Pacific. Nalanda and the other universities, by their achievement and their fame, provided an attractive model for the rest of Asia and beyond. In his 11th century survey of nations, al-Andalusi said: "The first nation [to have cultivated science] is India. . . . India is known for the wisdom of its people. Over many centuries, all the kings of the past have recognized the ability of the Indians in all branches of knowledge." It should perhaps not escape our notice that this was written by an Islamic scholar in Spain.

Concluding words

One of the deepest ideas shared by ancient civilizations was that of a universal order. All three of the civilizations we have covered to this point felt that the eternal rules and relationships used by the gods to create all things can be revealed through mathematics. Science was bound to prosper in these cultures.

Until quite recently, this idea was associated in its ancient form only, or overwhelmingly, with the Greeks. Egypt and Babylon had their mathematical systems, certainly, but these were judged of antiquarian interest. India, meanwhile, barely registered in importance and China not at all. Archeological evidence for the importance of India in the history of mathematics was reinterpreted by more than a few authorities as actually belonging to the Greeks or the Hebrews. Such was true even of the ten numerals that we continue to incorrectly call "Arabic." A European tradition running back to the 16th century assigned a Greek origin to these – despite the clear and repeated identification of them as Indian in many earlier works. The history of favoritism granted to Greece is complex but also definite. In part, it relates to European chauvinism, which claimed the Greeks as "western" and, since the Renaissance, the role of Greek and Latin as languages bearing "eternal wisdom." By the 19th century, the "Greek miracle" in science most of all had become an ingrained trope of Western culture.

The Greeks themselves had something to do with this too. Herodotus, that great travel writer of the 5th century B.C., is the one to have given us the name "India," from the Sanskrit *sindu* (river) applied to the Indus. How did he speak of India? As "the furthest region of the inhabited world towards the east." His passages contain intelligent comments about the people, clothing, and so forth. Yet they linger far more on the country as a land of wonders: ants that gather gold, tribes of ravenous cannibals, trees that give forth wool, animals of gigantic size. To classical Greek authors who wrote of it, India formed a fantastic realm at the edges of the Earth, where nature ran riot, creating monsters and marvels that were proof of an exotic primitivism.

Herodotus must have known something of the connections that had existed between India and the Near East, not least Babylon, for over a thousand years. Greece's own debt to Babylonian science and astrology, after all, was enormous. Moreover, the Persian (Achaemenid) Empire with which Greece had constant contact stretched from western Turkey to the Indus River, and this remained the case down to Alexander the Great's own day. Greek soldiers, sailors, traders, and physicians served in the Persian royal court, where officials and thinkers from all parts of the empire, including India, came into routine contact. We even find that contingents of Indian troops were part of the Persian army that invaded Greece in 480 B.C. Pythagoras and the Hindus both held the belief in the transmigration of souls, while the former also refused to commit his mathematics to writing, choosing oral poetry as his medium of expression.

Like many ancient peoples, the Greeks did not readily admit their debts to others or admit them at all. The same was true for Egypt, Mesopotamia, and India: we have no works from any of these nations telling of the extensive and profound things they learned from one another. Scholars have been forced to find such evidence in physical objects, exchanged through trade, in linguistic factors, and in similarities of thought, technology, and method that are interpretable as signs of intellectual borrowing. Often there are suggestions instead of hard data.

Thus, it is one of the more striking things confirmed by recent archeology that the ancient world was anything but a collection of self-contained peoples, hugging their respective river valleys. Instead, commerce was everywhere, essential to prosperity. There existed a constant circulation of ships, caravans, goods, people, technologies, and, therefore, ideas. This does not mean each civilization was completely welcoming of all things foreign. Influence was always selective, though never planned. The mathematics and sciences in Egypt, Mesopotamia, and India remained distinct, expressive of the particular demands and natural settings of their respective urban centers. Nonetheless, forms of circulation were an aspect of all three cultures and lead us to assume today considerable interconnection.

Such connection has been required to build the base from which modern science eventually could evolve. We have mentioned in this chapter several instances of this. We will have much more to say about it further on. The influence of Indian mathematics on later times we know for certain by the translations of Indian works into Arabic, then into Latin. The flow of this knowledge into Europe, and its adaptation into new works in Latin, yielded the essential basis for all that came after. In the end, Newton's comment about the glories of cosmic order might be said to owe as much to Indian, Islamic, and Greek mathematics as to his own genius. Indeed, he is also the one to have famously said, adopting the sentence from the 12th century scholar Bernard of Chartres: "If I have seen farther, it is because I have stood on the shoulders of giants." Giants, we would say, and Newton would agree, who lived in lands reaching from the eastern Mediterranean to South Asia.

Note

1 They have even been "found" to contain many concepts of contemporary scientific thought, such as those of quantum physics, modern cosmology, human physiology, and more. Such interpretations are controversial, to say the least, and have been strongly discounted by many scientists.

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5 The Greeks and science

Powers of discovery and inheritance

> But the whole vital process of the earth takes place so gradually and in periods of time which are so immense compared with the length of our life, that these changes are not observed, and before their course can be recorded from beginning to end whole nations perish and are destroyed.
>
> Aristotle, *Meteorology*

Many people die in the *Iliad*. Homer's tale of the Trojan War is horrendous in its carnage. The quality of bronze weapons had reached such a point that sword cuts are all fatal. Out of 106 spear injuries, 80% bring death. Of those warriors hit by arrows, barely half survive, and the rate is no better for those struck by daggers, hammers, and shields.

It is not surprising, then, that among Homer's heroes are the "god-sent healers." It was widely believed in later centuries that Homer was himself a physician. He tells how Menelaus, husband of Helen, was tended for an arrow wound by the physician Machaon, who "deftly applied the healing salves." When Machaon himself is later wounded by "a triple-barbed arrow," the Greeks are stricken with fear. Idomeneus, a powerful Greek soldier, begs the famous Nestor to quickly take Machaon back to the ships in his chariot for protection. "A physician is worth more than several other men together," he says.

The *Iliad*, we are told, is a story of rage, honor, mortality and hope for immortality. But it is also an epic steeped in science and technology – metallurgy, shipbuilding, civil engineering, astronomy, the biology of blood and broken limbs, and also, lest we forget, the invention of a great machine, hollow, in the shape of a horse.

Homer lived around 700 B.C., according to modern scholars. The stories he tells and the details he reveals, however, are much older. We know this early in the *Iliad* because all the weapons are made of bronze. In the region of the eastern Mediterranean, Egypt, and Mesopotamia, the Iron Age began about 1300 B.C. and continued to approximately 500–300 B.C. (depending on one's criteria). Homer, therefore, came late in this age, yet the Homerian world, including its scientific culture, reaches back before it had even become fully established. The realities of the Trojan War date to what is known as the Mycenaean Era, named for the great city of Mycenae, whose prominence lasted from roughly 1600 B.C. to

1100 B.C. (late Bronze Age). It is an era of warring city-states, sophisticated craft- and metal-work, grand palaces enclosed within massive walls. At once brutal and refined, it defined an earlier civilization to that of Plato and Aristotle, yet one that deserves our attention as well.

Background

Ancient Greece lay at the intersection of three continents – Asia, Africa, and Europe. From the earliest part of the Mycenaean Era to the end of the Hellenistic period 2,000 years later, Greek civilization was largely based on the sea and the connections it provided to the lands and peoples of the region. The Greeks were seafarers and traders, even more than they were farmers. And as such, they were in continual contact with other societies.

This was a matter of necessity. The Greek mainland is a mountainous, rocky peninsula. Bordered on three sides by ocean, it includes more than 1,400 islands and more than 12,000 km of rugged coastline, with many natural harbors (Figure 5.1). Only a small part of the country could be farmed; timber was never abundant. After about 900 B.C., the population dramatically increased, and Greek city-states soon began to send out expeditions that established colonies all over the Mediterranean. By 550 B.C., Greek settlements had spread to the coasts of Asia Minor, North Africa, southern Italy, Sicily and from coastal Spain to the south rim of the Black Sea. Above all, the region of the eastern Mediterranean where the Greeks did a majority of their trade and fought most of their wars was a great blending of peoples: Egyptians, Babylonians, Assyrians, Phoenicians, Lydians, Thracians, Illyrians, Hebrews.

Greek society thus grew up in a region of vibrant international connection and exchange. Historians of science have increasingly emphasized the degree to which the Greeks adapted material from other peoples. We have seen in previous chapters that when it came to inventions and technical knowledge, the tendency to borrow and adapt was not merely common among ancient civilizations but endemic. Greek thinkers were surrounded by societies already thousands of years old that had developed great bodies of knowledge of proven value. Herodotus tells us in his *Histories* (5th c. B.C.) that the Greeks adopted their gods from Egypt and accepted refugees and émigrés from there who "taught many things." The great 3rd century B.C. astronomer Hipparchus used observations on star positions and planetary movements recorded by the Babylonians, and these were subsequently adopted by Ptolemy, who mentions the fact in the *Almagest*.

What the Greeks did with the material they borrowed and what they invented on their own amounted to a magnificent flowering of pre-modern science, one that came to have immeasurable impacts over the next 1,500 years.

The Mycenaean Era: Bronze Age achievements

Yet they did not entirely lack their own predecessors. The Mycenaeans built a rich and vital civilization well before the age of Pythagoras and Plato. A few words,

Figure 5.1 Map of ancient Greece, showing cities and locations discussed in the chapter.

therefore, are needed on this earlier era of Greek culture, for which Homer is one of our best informants. Other information comes from clay tablets, mostly lists, accounts, and inventories, written in Linear B, a script adapted from Linear A (used by the Minoans on Crete, and still undeciphered).

The *Odyssey* describes the castle-metropolis of Mycenae as a powerful state, with nearby plains of "great plenty, and therein is meadow-sweet and wheat and barley, and oats with their white and spreading ears" (Book 4). Mycenaean cities were fortresses built mainly upon hills. They were surrounded by farmed lowlands, planted with olive groves. Homer speaks of "meat and drink" offered to Odysseus when he visits a new land, but we hear more of "wheaten bread in baskets" and "wheat and barley, which are the staff of life." There are passages that also tell of "pear-trees and pomegranates, and apple-trees with bright fruit, and sweet figs, and olives in their bloom." Core crops were, therefore, grains, fruits whose trees grow well in rockier, sandier soil, grapes, and olives. Olive trees are native to Greece but required much care: roughly 20 years of growth are needed before a tree will bear fruit and then only does so every two years.

A warrior elite ruled each city, with a king and court of advisers and soldier-commanders at the helm. There was frequent war and preparation for war. Literacy existed mainly among priests, merchants, and scribes. Mycenae was ruled by Agamemnon, "lord among men," leader of the Greeks in their siege of Troy. Yet, like all the citadel towns, it came to a fairly sudden end. A period of decay began after about 1250 B.C., with most cities burnt and abandoned by 1000 B.C. Why and how this happened remains unknown. Historians refer to a possible invasion by the Dorians, while Egyptian inscriptions suggest "sea peoples" overran Greece, Crete, and Asia Minor in the 12th century B.C. but just who they were and where they came from is a mystery. Such a clear break, however, makes it necessary for us to examine this society and its achievements separately from those of the Classical and Hellenistic era.

Mycenaean technology

Mycenaean swords and battle axes have been found in the Near East, the Caucasus, and many parts of the Mediterranean, confirming that such weaponry was widely recognized for its quality and served as a product of extensive trade. Bronze work defined an area of special attention, in fact, as Homer tells us. Mycenaean soldiers wore full body armor, with thin plates hinged and lashed together by leather straps. There is little copper in Greece and no tin, so these metals were imported, probably from Cyprus and Anatolia, with weapons manufactured in abundance.

Another technological height was civil engineering. Mycenaeans built and maintained an extensive road system linking the different city-states on the Greek mainland. This meant building many bridges over streams and ravines. Such bridges used a corbel system, adopted from palace architecture. In this system, stones at each new upward level are slightly cantilevered out over the underlying one so that the gap to be spanned is progressively narrowed until a final series of timbers or a stone slab can be put on top to complete the bridge. These structures rarely spanned more than 2.5 m (8.3 ft) but then they didn't have to. Their archways provided enough of an opening for streams to pass through. That dozens of these bridges were kept in good order shows that land-based travel, communication, and also conflict were central cultural aspects.

The most well-known expressions of Mycenaean engineering, however, are the remarkable phenomena of cyclopean masonry and the elegant beehive tombs or *tholos*. Cyclopean walls represent an early stage of palace construction and involved huge blocks of limestone conglomerate (Figure 5.2) only lightly worked and set without mortar. Such blocks were roughly fit together, with spaces between them filled afterward by smaller stones and clay. Stones are on the order of 2 m (6.6 ft) long, 1–2 m (3.3–6.6 ft) wide, and 1–1.5 (3.3–5 ft) tall, weighing 2–5 tons. Larger stones are up to 6 m (20 ft) or more in length and 20–50 tons. They are not merely enormous but breathtaking. The term "cyclopean" is an ancient one, reflecting belief that the mythic giants, children of the god Poseidon, had placed them. Blocks of nearly similar size were certainly excavated by the Egyptians long before, so these works are not unique. However, different (unknown) methods to maneuver them must have been used by the Mycenaeans, who did not have the open space or any where near the manpower that the Egyptians did. Most blocks

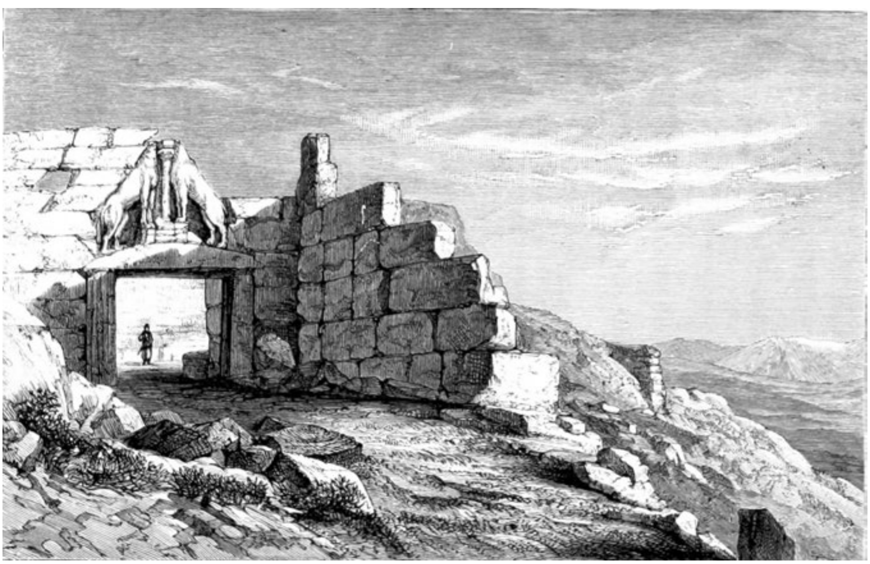

Figure 5.2 The Lion's Gate entrance to Mycenae, showing the two facing lions separated by a pillar, and huge, cyclopean stones used to build the protective outer walls around the city.

Figure 5.3 Photograph inside the Treasury of Atreus, a *tholos* or beehive tomb at Mycenaea. Well shown is the tapering, pointed shape of the structure and both the shaping and sizing of the stones to create a smooth wall for fresco painting and other decoration.

show no signs of quarrying, so were derived from surface country rock, probably as loose boulders.

Tholos are tombs built using an advanced method of corbelling, whereby stones were shaped and sized to create a bullet-shaped structure, narrowing upward to a final peak (Figure 5.3). Stones were tightly fit together and abraded to create a smooth inner surface, this being coated with sumptuous decoration in gold, silver, and bronze or with a stucco-type covering on which frescoes were painted. At the tomb entrance, columns of green serpentine and red marble were placed, along with a decorative frieze also of marble and capitals in Egyptian style. Visually, this would have been stunning. No fewer than nine *tholos* exist at Mycenae itself, dating from the 15th and 14th centuries B.C. The most impressive, called the "Treasure of Atreus," is 13.5 m (45 ft) from floor to peak. Though looted in ancient times, the tombs have still yielded many valuable artifacts, including gold death masks of their occupants.

All of this suggests a society rich in technology but relatively poor in science. Aside from their obvious talents in civil engineering, metallurgy, and also in shipbuilding, the Mycenaean people were not much interested in the study of nature or in recording any such study they might have done. Their scientific culture depended a good deal on crafts and arts adopted from surrounding peoples. Many of the items found at Mycenae – gold plates, vases, jewelry, daggers, buttons, ornaments – show magnificently swirling motifs and detailed, delicate patterns of the highest craftsmanship, similar to those of the Minoans.

Mycenaean geography

To understand what views of nature Mycenaean Greece held, we turn again to poetry. This means Homer and also his probable contemporary Hesiod.[1] The writings of these two poets are believed to have expressed aspects of life and intellect handed down orally from the late Bronze Age. What, then, do they tell us?

Concepts of the Earth found in Homer are those of the Babylonians but simplified. They appear in Book 18 of the *Iliad*, in a passage on the images forged into Achilles' shield by Hephaestus. The Earth is a flat, circular disk surrounded by a great "river," Oceanus, the primal ocean. Based on geographic features in the *Iliad* and *Odyssey*, we find the lands inside this ocean included Greece, Macedonia, Turkey, the Levant, North Africa, Ethiopia, and Cimmerii (northwestern Europe). There were also the known seas of the Mediterranean, Red, and Black, and the underworld of the dead. The most distant lands, apparently near the edges of the Earth, were Ethiopia, where the gods went to feast, and Cimmerii, which we will discuss in a moment.

In the *Odyssey,* meanwhile, Book 11 has the hero following directions provided by Circe to sail beyond the Pillars of Hercules (Gibraltar):

> We got into the deep waters of the river Oceanus, where lie the land and city of the Cimmerians, who live enshrouded in mist and darkness which the rays of the Sun never pierce . . . the poor wretches live in one long melancholy night.

It is tempting to interpret this land of winter gloom as the northern British Isles or Scandinavia, where the sun stays low to the horizon during the winter months. It is intriguing to match this with the finding of Mycenaean vases in Britain.

Hesiod, meanwhile, gives us something more. His *Theogony* tells the origin of the universe out of primal chaos and the succeeding battles between the gods and titans for supremacy. Zeus himself engages an epic struggle with Typhoeus (lines 860–865):

> . . . and the huge earth groaned. And flame shot forth. . . . A great part of the huge earth was scorched by the terrible vapor and melted as tin melts when heated by men's art in channeled crucibles; or as iron, which is hardest of all things, is softened by glowing fire . . . and melts in the divine earth through the strength of Hephaestus. Even so, then, the earth melted in the glow of the blazing fire.

This is clearly a volcanic eruption. Typhoeus, in fact, was hurled to Earth and chained there, with Mt. Etna – among the most active volcanoes in the Mediterranean – rising from the melted rock and soil above his mouth.

Homer's robots

Did Homer write science fiction? He sings of machines with intelligence, built to serve. "Robot" seems the best term for these creations in his tales.

In Book 18 of the *Iliad*, Achilles' mother pays a visit to Hephaestus, god of the forge, asking for a set of armor her son will wear against the Trojans. Hephaestus cannot say no, for Thesis is his foster mother, who rescued him when abandoned by his mother (Hera) for his lameness. He hurries to make himself presentable. In doing so, he has help:

> Handmaids ran to attend their master, all [of them] cast in gold but a match for living, breathing girls. Intelligence fills their hearts, voice and strength their frames, from the deathless gods they've learned their works of hand. They rushed to support their lord as he went bustling on and lurching nearer to Thetis . . .

Hephaestus is an elegant inventor. The scene, however, has a sad irony, showing an orphan male god surrounding himself with imitation females. The ugly master is served by beautiful virgins, whose purity and loyalty are the signs of their artificiality.

Turning to the *Odyssey*, we see a passage in Book 7, where Odysseus, washed ashore in the land of the Phaecians, arrives at the gates of King Alcinous' palace to find:

> Walls plated in bronze, crowned with a circling frieze glazed as blue as lapis. . . . And dogs of gold and silver were stationed either side [of the door], forged by the god of fire with all his cunning craft to keep watch on generous King Alcinous' palace, his immortal guard-dogs, ageless, all their days.

Hephaestus' work, again, this time with the goal not of beauty but of power. They are Homer's sign that this is the home of a worthy king, who will aid Odysseus perhaps in unexpected ways. And he does. Alcinous says to him:

> And tell me your land, your people, your city too, so our ships can sail you home – their wits will speed them there. For we have no steersmen here among Phaecia's crews or steering-oars that guide your common craft. Our ships know in a flash their mates' intentions, know all ports of call and all the rich green fields. With wings of the wind they cross the sea's huge gulfs, shrouded in mist and cloud – no fear in the world of foundering. . . .

It is an ancient dream, that machines will give mortals transcendent powers. These ships of the Phaecians are moved not by the gods but by some force of their own. Today, they have a clear parallel: the driverless car, a promised technology. In the modern world, the robot comes with an essential dilemma: to gain a new degree of freedom, we must give up an equal degree of physical control.

Classical and Hellenistic Eras: the "golden age" of Greek science

The flowering of Greek scientific culture begins in the 7th–6th century B.C. We know the names of many Greek thinkers starting from this period, since they appear in later works that have been preserved. This is not wholly unique, since we also know the names of some Babylonian, Egyptian, Chinese, and Indian thinkers who lived about the same time. But nowhere else do we find so many abstract scientific thinkers on geometry or planetary motion given as much apparent fame and attention as in Greece.

The huge impact that Greek scientific culture came to have cannot be doubted. Indeed, no single thinker in the history of science has had an influence equal to that of Aristotle. Such impact on later ages is due to four essential factors:

1 The Greeks' ability to make excellent use of much older scientific traditions, particularly those of Mesopotamia and Egypt.
2 The creative ingenuity of Greek thinkers to extend this older knowledge in many new directions and to develop new fields as well.
3 The ideas in Greek society that urged individuals to pursue the study of natural phenomena, explanations of them, and the documenting of this work in the form of books and to become teachers, encouraging others to do the same.
4 The systematic collection, translation, and expanding of this scientific knowledge by Islamic scholars, along with that from India, and its later translation into Latin.

Historians have identified the beginnings of Greek scientific thought in a specific group of thinkers from the port city of Miletus. Located along the southwestern coast of Asia Minor, or Turkey (see Figure 5.1), Miletus was a rich and safe port. Little more than a day's sail from Egypt, it was the Mediterranean port for major overland trade routes from Mesopotamia. Like the Phoenician cities, it had a thriving trade with many parts of the region and was powerful enough to establish colonies, specifically on the Black Sea.

The city was, therefore, a thriving center of exchange. It had wealth, influence, a diverse flow of traders and traded goods, and, we can easily assume, a magnetic attraction to those of intellect who could serve as teachers, tutors, translators, and advisors to those of wealth. It was at this time, too, that an Egyptian renaissance under the Saite pharaohs (26th Dynasty) took place, a period defined by attempts to recover and revivify the learning of the Old Kingdom. Much Egyptian science was rewritten and copied and added to the education of the upper classes. Given the scale of trade with Egypt and the constant movement of goods and people back and forth, Milesian scholars likely benefited from this rebirth of "wisdom." The city thus seems an excellent site where the gathering of knowledge from different peoples might give birth to new beginnings.

By the 5th century B.C., contributions to Greek science had spread from Miletus to other city-states, including Athens. Within another two centuries, this had expanded throughout large portions of the eastern Mediterranean, where Greek became and remained the language of scholarship even under the Roman Empire. The Romans, after all, for a variety of reasons, never adopted the sophisticated scientific and mathematical works that Greek civilization produced.

We might expect, given the many names of Greek scientific thinkers we know, that some original writings have come down to us. Not true. No original manuscripts survive from the period between 650 B.C. to 150 C.E.; not one. It is telling, in fact, that perhaps the richest find of Greek manuscripts (heavily used parts of them) from the Hellenistic period (323 B.C. to 150 C.E.) is the public garbage site at Oxyrhyncus in middle Egypt. In the whole of Greek science, there is nothing to compare with the *Edwin Smith Papyrus* nor with the Babylonian world map.

Greek scientific works were so often and widely used that early manuscripts were continually replaced by new generations of copies, which were replaced in turn. Original writings, furthermore, were also abridged for inclusion in popular handbooks and textbooks for teaching, plagiarized in writings by later authors, and selectively chopped up for use in compendiums, and these texts became more popular than the originals. Modern scholars have had much work to do comparing manuscripts of varied type, age, and even language to try and assemble authoritative versions.

What all this means, finally, is quite striking. If we are to be honest and to accept the evidence as it is, it means that names such as "Pythagoras," "Aristotle," and "Hippocrates" often refer not to a single author but to an entire textual community. With this in mind, we will discuss what seems, at least on the basis of consensus, the contributions associated with these names.

Astronomy

Thales, Anaximander, and rationality

Greek astronomy, and Greek science in general, has been said to begin with Thales, from Miletus. Thales is one of the authors about whom we only have second-hand information. He is famous because other famous authors mentioned him, not least Herodotus, Aristotle, and Plato.

Herodotus, who lived about 150 years later, credits him with a number of deeds and discoveries, in particular the forecast of a solar eclipse that stopped dead a major battle in Asia Minor on May 28, 585 B.C. Aristotle, a century later, says in *On the Heavens* that Thales proposed the Earth floats on water, like wood, and, in the *Metaphysics*, attributes to Thales the view that water defines the fundamental substance of all matter. Aristotle's *Politics*, meanwhile, tells the story of how Thales became wealthy on the basis of a prediction: "Having observed through his study of the heavenly bodies that there would be a large olive crop, he raised a little capital while it was still winter, and paid deposits on all the olive presses in Miletus and Chios [a nearby island], hiring them cheaply because no one bid against him."

The one critical mention of Thales, interestingly enough, is provided by Plato. In the dialogue *Theaetetus*, we are told the tale of how a Thracian slave girl makes fun of the famous astronomer for walking along and falling into a well while gazing up at the stars. Plato's comment is that philosophy can be both impractical and dangerous. Yet in the *Republic*, he mentions Thales as a great and "ingenious" inventor.

So we have fair evidence that Thales was indeed a key thinker. What happens when we consider the claims made on his behalf? As we've seen, eclipse predictions had been done by Babylonian and Assyrian astronomers based on numerical models, but forecasting the exact date of a total solar eclipse and *where* it would be visible lay beyond astronomical knowledge at this time. Thales could certainly have used, perhaps even improved, the Babylonian model to predict the year and gained fame for this. The image of Earth floating on water, meanwhile, was an element in Egyptian and Mesopotamian cosmogony and had been for over a thousand years. Predicting a bumper olive crop by astrono-meteorological signs seems possible in part, though this story too has the ring of legend.

Thales had several important students in Miletus. One of these, Anaximander, is supposed to have produced a map of the world, according to statements by Eratosthenes (quoted by others). Unfortunately, no description or visual record of it remains. Anaximander also gained credit for having introduced the gnomon (right triangle portion of a sundial that casts the shadow) from either Egypt or Babylon. The 6th century C.E. commentator Simplicius states that Anaximander promoted the concept of the infinite or "boundless" – *apeiron* in ancient Greek – as a primary principle and a reason for a plurality of worlds (planets) besides those visible in the solar system. As we have seen, both these latter ideas were present in Vedic thought as well at a much earlier date.

It is very difficult, that is, to make any firm or final statements about what these men said, wrote, or did. We can be fairly sure they earned their fame in significant intellectual ways, but if we accept some part of what later writers said about them, we must conclude that Thales and Anaximander were strongly influenced by Egyptian and Babylonian science. Those who lived closest to the time of these individuals, especially Herodotus and Aristotle, do agree they practiced a style of rational thought that was less developed elsewhere. This form of thinking sought by forms of logic to discover the ultimate physical nature of the universe, and to do so it relied on wholly materialistic explanations of natural phenomena. In other words, Thales and Anaximander (plus several other "pre-Socratic" thinkers) had no use for supernatural forces to generate these explanations. Modern scholars have argued about how much importance we should give to this. Is it really the moment in human history when science first breaks free of religion and establishes itself as a separate realm of thought?

There are problems with such a view. The assumption that in all other scientific cultures astronomy was always dominated by a religious goal or a mystical, astrological component simply isn't true. Precise observations and arithmetic relations were also devoted to practical purposes, like accurate calendar-making. Nor is it accurate or even possible, as historians now agree, to separate astronomy from astrology at this early period on the grounds that the latter was "unscientific." As we will see moreover, Greek astronomy was not entirely secular but had religious aims of its own.

Pythagoras

Mathematical astronomy in Greece is often said to begin with Pythagoras and the Pythagoreans (6th c. B.C.). Born on the island of Samos, a short distance from Miletus, Pythagoras seems to have travelled widely when still a young man to Egypt, and perhaps elsewhere, in an attempt to seek out different teachers or other sources of knowledge. At some point, he left Samos for the Greek colony of Croton in southern Italy. Here he established a kind of religious sect or brotherhood, mystical in part, demanding vows of silence, strict vegetarianism, and abstinence from all forms of writing. From a study of music, where he developed the theory of harmony based on numerical proportions, Pythagoras concluded that all things in the universe were the manifestations of numbers and could be so expressed. We have seen this same belief in Vedic astronomy of India.

Indeed, there are other similarities with Vedic thought. These include the concept of a universal oneness, the transmigration of the spirit/soul, and, again, the practice of transmitting all knowledge orally in order to protect its sacred qualities. Pythagoreans also had the idea of an invisible planet, a "counter-Earth," to help account for some eclipses, which Hindu astrology also poses in the tale of Rahu and Ketu. Most of these aspects are quite unique in the whole of Greek astronomy, suggesting the possibility of some connection with Vedic thought.

According to Aristotle, the Pythagoreans were the first Greeks to propose an actual physical model of the universe, in the form of circular bodies orbiting a central point. Interestingly, this model did *not* put the Earth in the center nor the Sun. Instead, a "hearth" of fire lay at the core, surrounded in order by the counter-Earth, the Earth, the Moon, Sun, and the five known planets, Mercury, Venus, Mars, Jupiter, Saturn.

The distance of each body from the central fire obeyed the proportions of musical intervals, giving rise to the idea of the "harmony of the spheres," a concept that remained alive down to the time of Kepler. This harmony was not a metaphor to the Pythagoreans. It existed as actual music, which the celestial bodies generated constantly as they followed their orbits. Unfortunately, it seems only Pythagoras could hear it.

Plato, Eudoxus, Aristotle

Plato, meanwhile, has long been considered a foundational thinker in Greek science, not for any discoveries or mathematical innovations, but for his ideas. Starting with him, we enter a domain where textual sources become available, though the degree to which they reflect the original work is rarely clear. In Plato's case, however, these sources are richly abundant.

Plato's writings are all dialogues, with Socrates as their protagonist. They thus carry the ironic message that knowledge can be derived (not only transmitted) by spoken words alone. Plato's one cosmological text, *Timaeus*, which had a huge influence on medieval Europe, is not secular but a distinctly mystical, moral, god-infused work. Plato sees a perfect order in the universe created by a great

Craftsman, an order that lies behind the imperfect world of appearances. It is also an order with a higher purpose, for it requires a rational, disciplined mind to grasp it, the only type of mind able to determine what is real and good in life.

The *Timaeus* may seem anything but scientific, but Plato's perfect, moral, and universal order is also densely mathematical, like that of Pythagoras. He says: ". . . and when [the Creator] set in order the heavens, he made this image eternal but moving according to number. . . ." Plato seems to adopt this idea directly from Pythagoras. But he also goes further. Motion in the universe means time, a specific kind of number, whether this be the lunar cycle, movement of the planets, or the rising and setting of the stars.

Moreover, geometry comes to bear. Each of the five fundamental substances in the universe – earth, air, fire, water, and aether – are associated with a unique geometric solid, in the way that a mineral has a specific crystalline structure. The solids are regular polyhedrons, with congruent faces (the cube is the first). The various combinations of these substances, and thus their polyhedrons, that make up physical matter, including the heavens; all converge on the most perfect shape of all: the circle, which has no beginning or end and is exactly the same at every point. This is the basis for all forms and motions in space. Indeed, the universe is itself a circle says the *Timaeus* and so are all its movements. The planetary circles (orbits) are distributed in simple intervals ("in ratios of two and three"), spinning in different directions and at different speeds but always "in due proportion."

Plato is said to have challenged all Greek astronomers to "save the phenomena." What did this mean? Finding ways to explain the paths of the planets in terms of *uniform circular motion*. These paths are irregular, roaming – the Greek word *planetae* means "wanderer" – such that they even reverse direction at certain times each year. Today we know this retrograde motion is an illusion, due to the Earth "passing" in its orbit the planets further out from the Sun, which, therefore, seem to go backwards. But when Earth is the center and all motion is circular, Plato's challenge demands much ingenuity.

The first to meet the challenge was one of Plato's students, in fact. Like his teacher, Eudoxus (ca. 395–337 B.C.), from the city of Cnidus in Asia Minor, studied many areas of knowledge – ethics, politics, mathematics, medicine, astronomy, as well as logic and philosophy. Following a pattern common to Greek thinkers, Eudoxus traveled to a number of cities in Greece, as well as to Egypt and Asia Minor, to learn from different teachers. It seems likely that this pattern helped to expose Greek thinkers to a variety of viewpoints and approaches, also increasing the chances that they would come in contact with the knowledge of other scientific cultures.

On the authority of other thinkers, Eudoxus was the foremost mathematician before Archimedes. He produced several major proofs, specifically of proportions, that were later adopted by Euclid for the most advanced books of his famous text, *Elements*. He appears to have composed two influential astronomical works, *Phaenomena* and *On Speeds*. The first was a fairly simple work, a kind of almanac, listing and describing the constellations, the major stars within them, and the type of weather associated with their positions in the sky. *On Speeds* was far more complex, laying out the author's mathematical structure of the solar system.

This system is difficult to describe, but highly imaginative from the standpoint of pure geometry. In the center stands a motionless Earth. Surrounding it are concentric spheres, with each planet having several spheres that determine its total motion. The planet is attached to a first sphere that spins at a certain angle. This sphere is attached to a second whose axis of rotation is tilted to that of the first. The rate of rotation is the same for both spheres but opposite in direction. If the two axes of rotation were the same, the planet would be motionless, but because they are tilted to one another, there is an up-and-down wobble. Now a third sphere, to which the second is attached, carries the other two around the Earth, generating a figure eight shape known as a hippopede (Figure 5.4), meaning "horse step," since horse's legs trace out such a figure in a trot or gallop. To account for the range of motion seen in the Sun, Moon, five visible planets, and stars, a total of 27 spheres was assigned. This included one for the fixed stars; three for the Moon and Sun; and four given to each planet.

The system is purely geometric, a kind of visual invention. Did it have problems? Most certainly. The nested spheres could not reproduce accurately the various retrograde curves unless inaccurate speeds were used for the motions of Mars, Venus, and Mercury. This and other problems made later mathematical astronomers look for different models. But no matter. Eudoxus had shown the power of mathematics to explain complex physical reality. From this point forward, with the major exception of Aristotle, Greek astronomy and mathematics would be inseparable.

In truth, Aristotle was to be the exception that created new rules. So influential was he, in so many areas of science, that he deserves his own section in this book

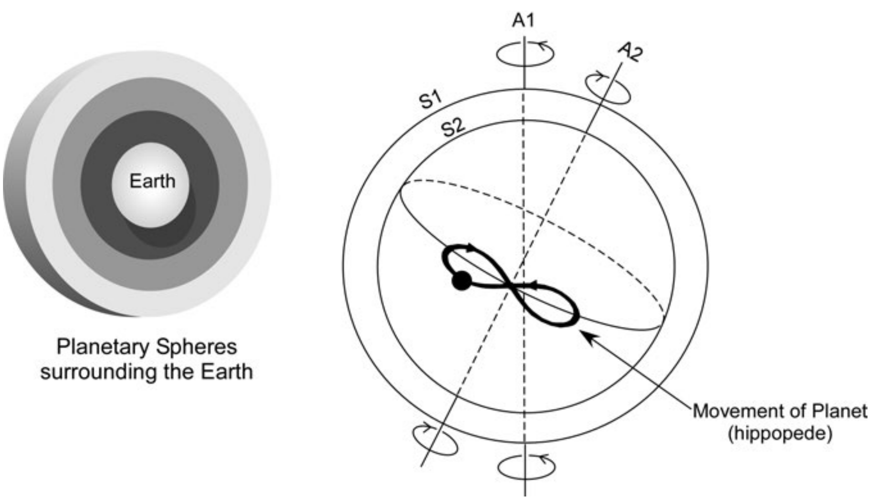

Figure 5.4 The basic model of the universe invented by Eudoxus. Each planet is moved simultaneously by two or three spheres, their axes tilted to one another, so that a figure-eight motion resulted. Also see text for discussion.

(which he is given). Yet his impact on astronomy fits readily into any discussion of Plato and Eudoxus. He was also Plato's student and, like Eudoxus, opened his own school later on. This was the famous Lyceum in Athens, where many important pupils studied. His main work on astronomy is known today by its Latin title *De Caelo* ("On the Heavens"), since the oldest existing manuscripts date from the late European middle ages. Within this book, Aristotle barely uses any mathematics, preferring instead the use of logic to derive conclusions. He agrees with Plato, Pythagoras, and others who viewed the stars and planets as seats of divine presence. This, too, places him somewhat against the more secular mathematicians, yet it made him far more acceptable to both Islam and the Christian West.

Aristotle embraces the Eudoxian model (Figure 5.5). He accepts, as established fact, the spherical form of the Earth and the heavens generally and also the circle

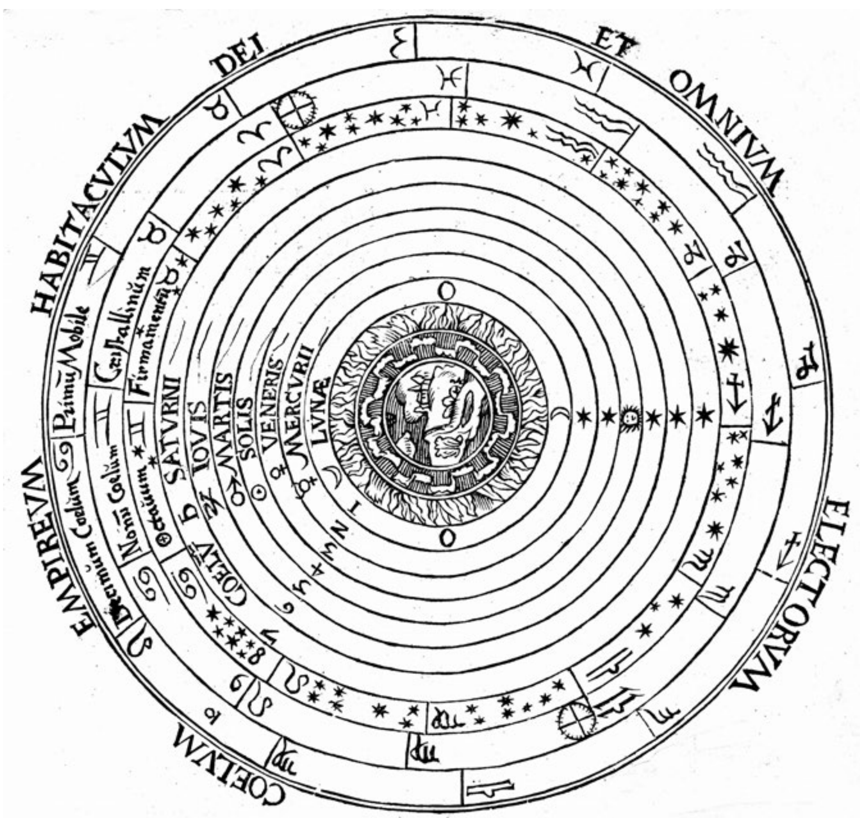

Figure 5.5 Aristotle's model of the universe, based on 55 concentric spheres, remained accepted by Islam and Europe until as late as the 16th century, as shown by this Christianized version of it in Peter Apian's *Cosmographia* (1544). Note that the order of the celestial orbs around the immobile Earth includes the Sun (solis) in fourth position. © Universal History Archive/Getty Images.

as the primal path of all motion. His own adaptation of Eudoxus' system is given in his work *Metaphysics*. There are further complexities: more spheres are needed (the total now becoming 55), while the movement of some spheres must be stopped for others to work. There is a physics of motion here, starting with the outermost sphere; that of the fixed stars, whose own circular movement is conveyed to the inner spheres by mechanical action. It is a system that contains godly work of some kind yet is also fully mechanical.

Aristarchus and Eratosthenes

Greek astronomy, therefore, produced a number of competing systems to model the solar system and universe. This was truly unique. Other civilizations, from Egypt to China, produced variations of a very limited number. The Greeks geometric invention yielded material of enormous importance in modernizing the heavens.

Among these competing hypotheses, one was itself unique. Aristarchus of Samos (ca. 330–250 B.C.) brought forth a truly heliocentric – Sun-centered – system. The system put the seven known planets all in their correct order, with the Moon orbiting the Earth and Saturn the furthest away (Figure 5.6). Equally impressive, he proposed that the rotation of the Earth accounted for the rising and setting of the Sun. The stars do not seem to move or shift as the Earth runs its yearly course around the solar body, he said, because they are too far away, enormously farther than other thinkers believed. All of these hypotheses we know to be true today. They were, however, attached to other ideas that we know to be false, e.g. that the Sun was the immobile center of the entire universe and that the stars are all embedded in single celestial sphere.

Aristarchus's system had to vie against the geocentric model supported by Plato, Eudoxus, Aristotle, and later, Hipparchus. The combined authority of these

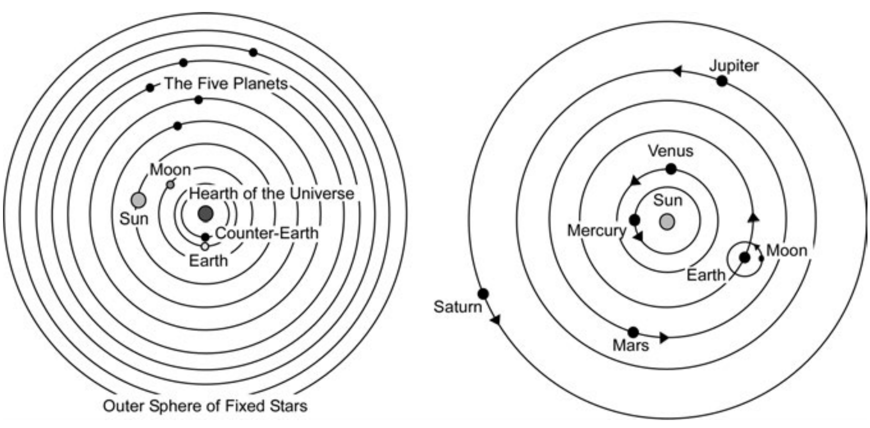

Figure 5.6 Diagram showing models of the universe created by Pythagoreans (left) and Aristarchus (right). Note that Aristarchus' model has the planets in the correct order.

thinkers proved too much. Plutarch even said (four centuries later) that Aristarchus was nearly arrested for impiety because of his hypothesis, but this is unlikely at best. His model certainly obeyed Plato's demand that everything be based on the circle.

Born on the same island as Pythagoras, Aristarchus was apparently influenced by at least one of the Pythagoreans, Philolaus of Croton, as we learn from Aristotle, Aristarchus' contemporary. We are certain of his heliocentric views as they are mentioned by many later writers, most of all by his other contemporary, Archimedes (287–212 B.C.) who speaks of this theory in his book *The Sand Reckoner*. We also learn from Archimedes that Aristarchus wrote a number of important works both on astronomy and mathematics. All but one of these have been lost. The one work attributed to Aristarchus, *On the Sizes and Distances of the Sun and Moon*, makes no mention of the heliocentric view. It contains an error, however, in the estimated diameter of the Sun, given as 2° (of the 360° of the celestial sphere). In *Sand Reckoner*, however, Archimedes attributes to Aristarchus the correct number, 0.5°. So perhaps Aristarchus wrote *On the Sizes and Distances* early in his career and then later matured in his calculations and hypotheses. That he did attain the right answer shows he was a first-class user of geometry and that this could have helped heliocentrism if so many weren't against it.

Another part of Aristarchus' fame is well deserved: his influence on Copernicus, 18 centuries later, along with Philolaus. How do we know this? Because Copernicus himself says so, in a two-page section that he removed from his famous book *On the Revolutions of the Heavenly Bodies* before it was published in 1543. The passage has been discussed by several scholars, including Sir Thomas Heath and Edward Rosen. It shows beyond any doubt Copernicus was a thorough reader of the classical literature:

> The motion of the Sun and Moon can be demonstrated, I admit, also with an Earth that is stationary. This is, however, less suitable for the remaining planets. Philolaus believed in the Earth's motion for these and similar reasons. This is plausible, because Aristarchus of Samos too held the same view according to [those] who were not motivated by the argumentation put forward by Aristotle. . . .

Given that the most difficult idea in the heliocentric view to accept was not the Sun's position but the Earth's motion, this is an important passage. Important, too, that Copernicus did not destroy it, but replaced it in his own, personal copy of the book.

It turns out, however, that Aristarchus was not a single bright candle that flared and went out. Plutarch, in *Platonic Questions* (Question VIII), tells us that Seleucus (2nd c. B.C.), a Hellenized Babylonian astronomer from the city of Seleucia in Asia Minor, actually "proved" the heliocentric model. He fails to inform us what kind of proof it was. He does include this fascinating statement: "Plato, when he grew old, repented that he had placed the Earth in the middle of the universe, which was not its place." Meanwhile, Strabo (ca. 64–25 C.E.) in his great work *Geographia*, says that Seleucus was one of the four great astronomers of the

Chaldeans (Babylonians) and was the one to have discovered that the ocean tides are caused by the Moon. Again, we have no more information than this. We can guess that recording of tidal and lunar cycles was responsible, but this is a guess. Strabo does mention a key fact: Seleucus was used as an authority by Hipparchus. Given Hipparchus's fame, this shows Seleucus was well known and that connections with Mesopotamia were probably quite strong.

Before taking up Hipparchus though, we should look at the contributions of Eratosthenes (276–194 B.C.), best known for his excellent use of geometry to calculate the Earth's circumference. We owe a good deal to this widely learned man, who wrote now-lost works on astronomy, mathematics, geography, music, and poetry and who was appointed head of the Great Library at Alexandria. He was born in Cyrene, in present-day Libya, and was another thinker who studied under various teachers in different cities, mainly Athens and Alexandria. A good friend of Archimedes, he is credited by other writers with having invented, or developed from Eudoxus, the first system of latitude and longitude, which he apparently employed on an actual map of the world, now lost. He is also said to have calculated the tilt of the Earth's axis (23.3°) and to have come up with the idea of a leap day to help even out the calendar year. Yet, despite such achievements, he is best known for determining the circumference of the Earth.

Figure 5.7 shows the reasoning of Eratosthenes. In basic terms, he used the fact that the summer solstice represents the day when the Sun is at its highest point in the sky, i.e. as close to directly overhead as it can be. Because of the tilt of the Earth, the Sun's rays will be perpendicular to the Earth's surface at the latitude of 23.3° not the equator. Eratosthenes had been told or he observed that this occurred in the Egyptian city of Syene – in a shallow well, the rays of the Sun cast no shadow on the solstice. In Alexandria, however, a standing obelisk displayed on that same day a shadow that sloped 7.2°. Assuming that the Sun's rays in both places are parallel (the Sun is far away), this angle is equal to that subtended by radii of the Earth at Syene and Alexandria, as shown in Figure 5.7 This means the distance between the two cities, M, corresponds to the angle 7.2°, and so if we divide this angle into 360° we find out what part of the total circumference M represents. Dividing 7.2 into 360, we get 50; so 50 × M gives us the Earth's circumference, which Eratosthenes determined to be about 39,350 km or 24,593 miles, within 1% of the modern figure. In truth, he did not use kilometers but the stadion, the length of an athletic stadium, as his unit of measure, which adds a bit of uncertainty, since there seem to have been several standards for the stadion. Modern scholars are quite willing, however, to give Eratosthenes the benefit of the doubt.

In a way, this uncertainty doesn't matter. Why not? Isn't an accurate determination needed, as proof of the method? Not entirely. The method is clearly correct; poor measurement of M doesn't affect this in the least. For it to be correct in every detail, the two cities would need to lie along the same line of longitude, so that no other uncertainties result due to oblique curvature of the Earth between the two sites. In fact, Eratosthenes believed that Syene and Alexandria *were* co-longitudinal (they are actually about 3° apart). But what Eratosthenes achieves with his demonstration is the raw power of mathematics, its ability to unravel key truths about

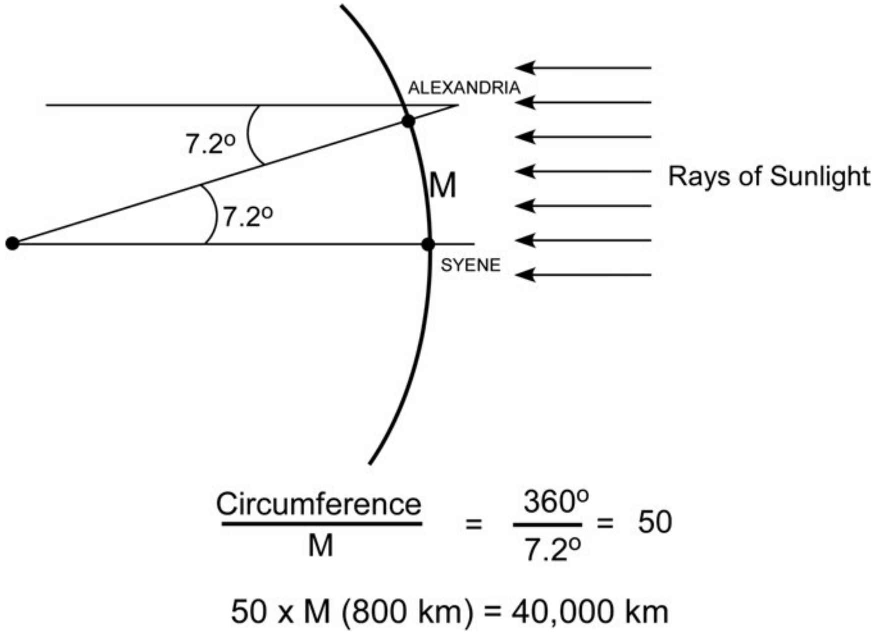

Figure 5.7 Diagram to illustrate the geometry used by Eratosthenes to measure the circumference of the Earth.

the universe. In this particular case, we learn the actual, physical size of the Earth, our home planet (for now).

Hipparchus and Ptolemy

We come now to Hipparchus, whom many scholars today consider to mark a great advance in all aspects of astronomy – observational, theoretical, mathematical, and instrumental. The observational dimension is essential; few Greek thinkers had been interested in recording celestial "data" regarding the positions of stars, planetary movements, occultations, transits, and so forth. Hipparchus realized the great value of such information, not least its importance for determining the validity of theoretical and mathematical models, as well as accurate estimates of celestial dimensions.

He was born, it appears, in the city of Nicaea, located in modern-day northwest Turkey, probably around 190 B.C. Very little is known about his life, except that he spent much of his career on Rhodes and that he traveled extensively for reasons that are unrecorded but which we can guess. The material he borrowed from Babylonian astronomy mostly likely came to him via translations. To make full use of it, he adopted the system of dividing a circle into 360° and each degree of arc into 60 parts. He also realized the high level of accuracy in the Babylonian cycle of solar and lunar periods.

With the help of star positions recorded by the "Chaldeans," by Timocharis of Alexandria 150 years earlier, and his own abundant measurements, Hipparchus made a striking discovery. He saw that the positions of the stars had changed over time. Whether this had been known before, in Mesopotamia, Hipparchus seems to be the first to explain it in physical terms. He said it revealed a shift in the axis around which the heavens rotated – best expressed, he felt, by a slow creep forward of the equinox along the ecliptic, through the constellations. Simply put, this meant that the equinoxes (when night and day are equal in duration) occurred slightly earlier each year. His term was "precession of the equinoxes," likely the title of one of his books. This motion is actually due to the Earth's own movement, the wobble of its axis due to its tilt (Figure 5.8). The precession was very slow; Hipparchus calculated it at about 2° every 170 years, indicating it would require 30,600 years for one entire precession (the actual figure is about 26,000 years). His discovery allowed him to determine highly accurate values, within less than 7 minutes of error, for both the tropical year (the time for an equinox to be repeated) and the sidereal year (the time for a particular star to return to a given position).

Hipparchus was fortunate. During his lifetime, he witnessed both a supernova and a solar eclipse. The first event was particularly important. According to later writers, the "new star" that appeared in 134 B.C. and changed in brightness led him to conclude that the fixed stars are not even fixed in number. He then turned once again to the Babylonian records and his own observations to construct a comprehensive star catalogue, listing about 850 visible stars, their positions in celestial latitude and

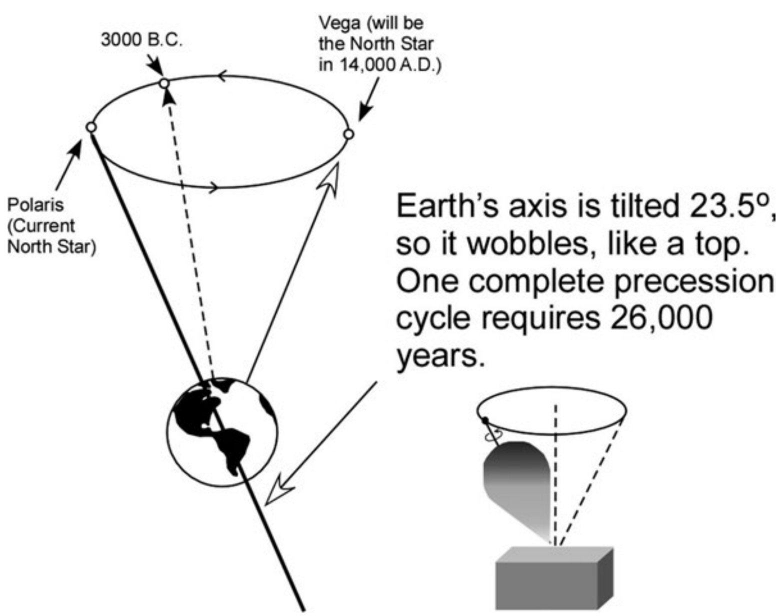

Figure 5.8 Diagram showing precession discovered by Hipparchus.

longitude, and also their levels of brightness based on a six-level system of magnitudes. This was the first such catalog that we know of in Greece. It is a major achievement, this attempt to precisely map the entire visible sky, motivated by the knowledge that it would be a key reference for the future. Some found this unfixing of the stars an act of impiety, as the heavens were deemed eternal and perfect. Hipparchus was never charged with anything, however. His books remained in circulation down to the time of Ptolemy, whose own work ultimately incorporated and destroyed them.

It makes sense to bring up Ptolemy's astronomy at this point, then. A good deal of it, after all, was taken or adapted directly from Hipparchus' work. Hipparchus' model for planetary motion formed the accepted version of the solar system for 300 years. What was this model, and how did Ptolemy refine it? The answers lie in Ptolemy's greatest work, which he called the *Megale Syntaxis* ("Mathematical Compilation") and which Islamic astronomers later renamed *Almagest*, from the Greek *megiste*, meaning "magnificent" or "majestic."

Hipparchus' model is shown in Figure 5.9. We see it has several elements: a large circle called the *deferent*, whose center is a point labeled the *eccentric*; a small circle, the *epicycle*, whose center moves along the deferent; the relevant planet, which is carried around the epicycle and the deferent; and the Earth, which is immobile. During the year, the planet's motion includes many orbits around the epicycle, which itself travels around the deferent. The Earth is off-center relative to the deferent. From its surface, we perceive the planet as larger and brighter for half the year (left side), since it is closer. If we imagine these movements in slow motion, we can more easily see how the planet will seem to move backwards at certain times, as it completes the lower half of the epicycle.

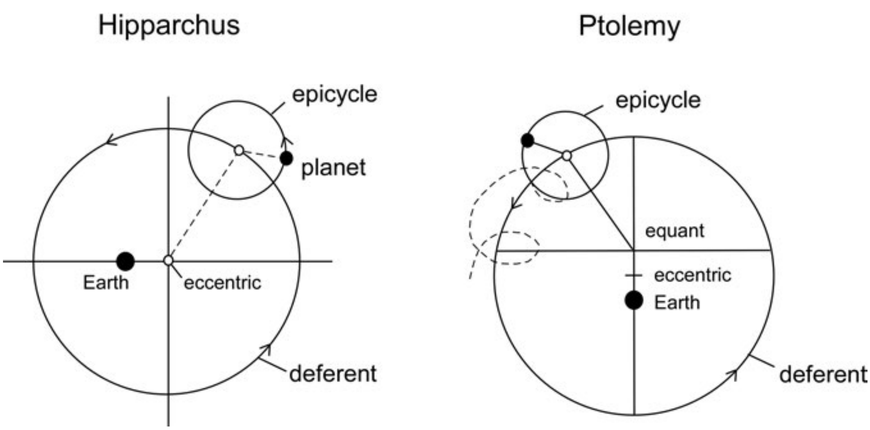

Figure 5.9 Models of planetary motion proposed by Hipparchus and the adapted version conceived by Ptolemy. In Hipparchus' model, a planet moves in a small circle (epicycle) whose center moves in a large circle (the deferent) around center (eccentric). Ptolemy modified this model to better match actual observations ("save the phenomena") by proposing that motion of the epicycle along the deferent is constant relative to a new point called the equant, with the planet tracing out the motion shown.

This model accounted quite well for Hipparchus' measurements of planetary movement, but it was not accurate enough for Ptolemy, who had the benefit of several centuries' additional observations, including his own. To save the model, and thus uniform circular motion, he introduced several new elements. Ptolemy realized that greater precision could be achieved if movement of the epicycle around the deferent was not uniform. It needed to speed up as it approached the Earth and to slow down as it receded. This would have meant abandoning the model, since this motion was non-uniform. But Ptolemy came up with an ingenious solution. As seen in Figure 5.9, he added a new point called the *equant*, on the opposite side from the Earth and an equal distance from the eccentric. Ptolemy hypothesized that where the eccentric remains the center of the deferent's circle, motion of the epicycle *along* the deferent is uniform relative to the equant. In short, the form of the deferent has one center, its motion another. Ptolemy provided a detailed geometric explanation of his model in the *Almagest*, taking up many pages. Perfect, of course, it wasn't. Yet it allowed its author to chart future positions of the planets with errors of less than five degrees, a considerable improvement.

Ptolemy's contribution did not end here. More a compiler than a discoverer, he brought to a high point others' work in several areas. The *Almagest*, as his most sophisticated work, includes chapters on the length of the year and month, theory of eclipses, discussion of planetary latitudes, and construction of the instrument known as the *astrolabe* for determining the positions of celestial bodies and thus casting horoscopes, among other uses. Ptolemy's star catalogue updates the positions in Hipparchus' version, adds 172 new stars (total 1,022), and lists 48 constellations, also from Hipparchus. It seems Ptolemy also collected a number of tables from the *Almagest*, modified them slightly, and wrote an introduction to them. This book, known as *Handy Tables*, gave numerical information useful for computing the positions of the Sun, Moon, planets, and stars, as well as eclipses.

This great systematizer produced a summary or digest of his own *Almagest* in which he felt it important to provide a discussion of the actual physical nature and dimensions of the universe. Here, in fact, we see this great systematizer fully accept the basic model, going back to Eudoxus, of the stars and planets comprising nested spheres. The Sun lay at an average distance from the Earth of 1,210 Earth radii, with the so-called fixed stars around 20,000 radii. Ptolemy's calculations suffered from a major error. He greatly underestimated the Earth's circumference – using not Eratosthenes' method but instead that of another famous teacher, Posidonius – which yielded a figure 28% too low (28,985 km). Using this number to attain the Earth's radius and multiplying it by 1,210, we get Earth's distance to the Sun to be 5.6 million km, somewhat less than the actual figure (known today as the astronomical unit or AU) of 149 million km.

One final work we'll mention here is Ptolemy's *Tetrabiblos* or "Four Books." Like all his other texts, this came to have enormous influence for many centuries. It is a volume on astrology and divination or rather a "demonstration" of how astronomical observations reveal to us "that a certain power emanating from the eternal ethereal substance is dispersed through and permeates the whole region about the earth, which throughout is subject to change, since, of the primary sub-lunar elements, fire and air are encompassed and changed by the motions in the ether, and in turn encompass and change all else, earth and water and the plants and animals therein," including human beings.

Greek and also Roman society had inherited a strong belief in such permeating powers of the heavens. After Alexander the Great's conquests of Egypt and Mesopotamia, the astrological traditions of these two civilizations became hugely popular throughout the Mediterranean region. It is apparent from parts of his discussion that Ptolemy's aim in *Tetrabiblos* was to establish a reference work so that readers might be able to better distinguish legitimate practitioners from the many charlatans that prowled the cities. Though non-mathematical, the author's discussion is no less rational and rooted in logic than anything else he wrote.

We have left off discussing Ptolemy's life, because almost nothing is known about it. It appears certain that he wrote most or all of his works in Alexandria, where he would have had access to whatever might have remained of the Great Library. Moreover, this city was by far the most intellectually cosmopolitan in the entire western and near eastern world at that time. Despite its riches, power, and size, Rome could barely begin to compete with the scientific brilliance of Alexander's namesake metropolis. Ptolemy's unequalled achievement, in creating works that would nurture varied scientific cultures for the next 1,500 years, was itself an expression of the height to which Hellenistic science reached in that great city.

Medicine

Ancient Greek medicine was dominated by two remarkable individuals, Hippocrates (c. 460–380 B.C.) and Galen (129–216 C.E.), who lived 700 years apart. Hippocrates appears the first Greek to take a rational but also holistic view, including consideration of such factors as diet, exercise, and mental condition, as well as environmental aspects. These were all expanded by Galen, who also ventured into other areas, such as anatomy. Historically speaking, Galen had the greater influence. But this is deceptive, since he had absorbed the greater part of Hippocratic thought from the beginning.

Hippocrates and his oath

Hippocrates was born on the island of Kos, off the coast of Asia Minor (Turkey), according to most accounts. It is believed that he was taught medicine by his father but also studied at the famous *aesclepieion*, or temple devoted to Asclepius, god of healing, on Kos. He is supposed to have traveled and practiced medicine in a number of places, perhaps as far away as Thrace. Almost certainly he established a school on Kos, which became an important center of medical learning. Kos and the nearby island of Cnidus were both early sites of scientific medicine and appear to have competed and collaborated with each other over time, since perhaps as early as the 6th century B.C.

In truth, so little biographic information exists in a reliable form that we cannot be sure of what Hippocrates achieved in his lifetime. It was considerable, as he is mentioned as an authority by Plato, who was his younger contemporary, and by Aristotle, who was about four years old when Hippocrates died. Neither author, however, quotes anything Hippocrates said or wrote. Nor do they discuss his ideas and methods. Roughly 70 medical works bear his name, yet we can't be sure how many of these he actually wrote and how many might have come from his teachers, students, and colleagues. Thus, as often in Greek science, when we mention the "Hippocratic corpus," we are actually invoking a textual community.

This corpus developed a theory of the body that was at once physical and immaterial. This was the theory of the four humors, or fluids: black bile, blood, yellow bile, phlegm. It was possibly adapted from the Pythagorean idea of the four fundamental substances, earth, air, fire, and water, each humor being associated with one of these (in the order given). This, however, was only the tip of an extensive and complex system of association. Each humor was linked to a particular organ (in order: spleen, liver, gallbladder, brain/lungs); to physical qualities (cold and dry; hot and moist; hot and dry; cold and moist); to the seasons and weather (e.g. black bile = winter); to influences of specific planets (black bile = Saturn); and to specific disease conditions and mental states (e.g. an excess of black bile in the body led to melancholy/depression). Illness according to humor theory had its most frequent cause in imbalances among the four humors, caused, for example, by eating the wrong foods, whose undigested remains would produce damaging vapors.

All told, humoral theory shared a number of aspects from earlier medical systems. Its linkages between fundamental substances or agents and organs, planets, seasons, etc. were similar to those in Bablyonian and Indus Valley medical thought. Recall that in the Old Kingdom, Egyptian physicians held a view of the body as a single entity whose primary action was to transport basic fluids—lymph, mucous, semen, air, urine, tears, saliva, as well as blood – through channels that connected all parts of the body together. The humoral paradigm does not seem particularly advanced over this. When we turn to Vedic medicine, too, we find a number of the same basic ideas underlying Hippocratic thought – the body as a holistic system; its link with the larger universe; the importance of empirical observation; the need for detailed descriptions of symptoms; and even the humoral theory itself, though in a somewhat different form (see Chapter 4). Hippocrates, in short, seems to have owed a great deal to surrounding civilizations.

Yet in those works that ancient authors all attribute to Hippocrates himself, we do find discussion that goes beyond these other medical traditions. Two specific examples are enough to show this. The essay "Airs, Waters, Places" begins by declaring: "Whoever wishes to pursue properly the science of medicine . . . ought to consider what effects each season of the year can produce; for the seasons are not at all alike, but differ widely both in themselves and at their changes." The physician should also take note of the winds and rain, and, "He must also consider the properties of the waters; for as these differ in taste and in weight, so the property of each is far different. . . ." When he arrives in a new town, a physician needs to take an inventory of environmental conditions regarding climate, air movements, water sources, soil composition, plus the lifestyle of the inhabitants (Are they heavy drinkers? Industrious? Poor?).

Such an approach strikes us today as informed and intelligent. Establishing baseline health conditions for a town or village or neighborhood seems like excellent, even essential, advice. Hippocrates, however, was a man of his age. He seeks, as did those in other medical traditions, to define universals in terms of how the four humors were affected by environmental elements. For example: in a locale "exposed to the hot winds . . . the heads of the inhabitants are moist and full of phlegm . . . most of them have a rather flabby physique, and they are poor eaters and poor drinkers. . . ."

But Hippocrates is also our contemporary in another sense. Or so we are told. The medical profession has modernized him by adopting his ancient oath, with today's medical students required or requested to swear allegiance by it. This modern version, however, is not quite the same as Hippocrates' own. Let us compare them, beginning with the original:

> *I swear by Apollo Physician and Asclepius, and Hygieia, and Panacea . . . that I will fulfill according to my ability and judgment this oath and covenant . . .*
>
> *I will use those dietary regimens which will benefit my patients according to my ability and judgment, and I will do no harm or injustice to them.*
>
> *I will give no deadly medicine to anyone if asked, nor suggest any such counsel; and similarly, I will not give to a woman a pessary to produce abortion . . .*
>
> *Into whatever homes I enter, I will go for the benefit of the sick, and will abstain from any voluntary act of mischief or corruption, including the seduction of women or men, whether they are free or slaves.*
>
> *Whatever I may see or hear in the lives of my patients, whether in connection with my professional practice or not . . . I will keep secret, considering all such things to be private.*
>
> *So long as I maintain this Oath faithfully and without corruption, may it be granted to me to partake of life fully and the practice of my art . . . But should I trespass and violate it, may the opposite be my fate.*

Next is the modern version, written in 1964 by the Dean of Tufts Medical School, Louis Lasagna:

> *I swear to fulfill, to the best of my ability and judgment, this covenant: . . .*
>
> *I will apply, for the benefit of the sick, all measures that are required, avoiding those twin traps of overtreatment and therapeutic nihilism.*
>
> *I will remember that there is art to medicine as well as science, and that warmth, sympathy, and understanding may outweigh the surgeon's knife or the chemist's drug.*
>
> *I will not be ashamed to say "I know not," nor will I fail to call in my colleagues when the skills of another are needed for a patient's recovery.*
>
> *I will respect the privacy of my patients, for their problems are not disclosed to me that the world may know. Most especially must I tread with care in matters of life and death. If it is given me to save a life, all thanks. But it may also be within my power to take a life; this awesome responsibility must be faced with great humbleness and awareness of my own frailty. Above all, I must not play at God . . .*
>
> *I will prevent disease whenever I can, for prevention is preferable to cure.*

I will remember that I remain a member of society, with special obligations to all my fellow human beings, those sound of mind and body as well as the infirm.

If I do not violate this oath, may I enjoy life and art, respected while I live and remembered with affection thereafter. May I always act so as to preserve the finest traditions of my calling and may I long experience the joy of healing those who seek my help.

It is not so easy, in the end, to claim Hippocrates as one of the moderns. Many changes are needed to make his famous oath acceptable in a secular era, where abortion is legal and viewed by many as a moral right and where doctors have risen in professional and social status to a level undreamed of in ancient times.

From Hippocrates on, Greek medicine accepted the humor theory but other innovations too. One of these was the basic clinical approach. This had four parts: to carefully observe all symptoms; to render a diagnosis best fitting these signs; to determine a treatment that best fits this diagnosis; and to observe the patient's recovery and use this "data" for future cases of similar illness. This rational approach, applied systematically, remains the basis of medicine to the present. Emphasis was also given to recording case histories for practice and teaching. Such are the signs of a highly logical, systematic approach to illness in general, one that was later adopted and taken further in Islam. It differed radically from the use of potions and spells so commonly employed by quacks and charlatans so numerous among the poor.

One area where Hippocratic medicine was eventually seen to be weak was anatomy. Study of the interior of the body was undoubtedly known through wounded soldiers and from dissection of animals by analogy, but Hippocrates stressed external signs. Human dissection was not practiced until the 3rd century B.C. in Alexandria and then it lasted a mere century-and-a-half before Rome outlawed it everywhere in the empire.

Galen

Galen has been called the Ptolemy of Greek medicine. This suggests his ability to culminate the best of what had gone before, to systematize it and extend its powers. So successful was he at this, that Galen's works, along with a great many derivatives assigned to him, were the primary source of medical knowledge in the West up to the 16th century. As late as the 1520s, expensive editions of Galenic works, complete with elegant woodcut illustrations, were being published.

Galen was most strongly influenced by the Hippocratic tradition but absorbed ideas from other schools as well. Born in Pergamum, a key intellectual center of the Hellenistic world, to a wealthy family with scholarly interests, he received an extensive education in philosophy, rhetoric, oratory, and other principal subjects before he began his medical training. It is fairly certain that he visited many parts of the eastern Mediterranean, including Alexandria, in order to broaden his knowledge of medical thought and practice. He began his career as a surgeon of gladiators, eventually settling in Rome while still in his early 30s, gaining a brilliant reputation and becoming personal physician to highly placed officials before being made the exclusive medical advisor to emperors Marcus Aurelius, Commodus, and Septimius Severus. His knowledge and treatments went strongly against existing methods in Rome, which used divination.

He improved classification of diseases and applied new methods of diagnosis. Unlike Hippocrates, he believed that knowledge of the body's organs was essential, since many illness developed there. Galen gave priority to the pulse and study of a patient's urine as diagnostic tests. Yet he also advised that all symptoms, no matter how seemingly trivial, should be noted.

His improvements to Greek and Roman medical understanding included new and more detailed descriptions of the skeletal and circulatory systems, the brain and nerves, and the heart. Using analogies from animal dissection, he greatly advanced knowledge about the trachea and lungs but also made several errors in other parts of the body. He separated venous and arterial bloods, saying they were different fluids, not part of a single system and that they originated in the liver and the heart, respectively. Along with the brain, origin of the nerves and provider of sensation, these two organs formed a tripartite human physiology. A key idea here was that the arteries and veins both contain blood not air or other fluids. From Hippocrates, Galen adopted the concept of dark, venous blood acting as a carrier of humoral imbalance, thus supporting the therapy of bloodletting. Finally, Galen was evidently among the most skilled surgeons of his day.

Perhaps most impressive, from the modern point of view, was Galen's use of experimentation and public demonstrations. He is known to have used a bellows to show the workings of the lungs (in a nonliving animal), though he actually attributed the pumping action to the heart. He also performed surgical "trials" on animals, e.g. for cataract removal. And in his public debates with other physicians in Rome, who believed that bloodletting would allow escape of the vital circulating "air," he demonstrated time and again that such a treatment left the patient quite intact.

The total size and scope of the Galenic corpus grew after Galen's own death in 203 C.E. While many uncertainties remain about his actual writings, Galen certainly brought to a peak the medical knowledge inherited, adapted, and advanced by ancient Greek civilization. In strict terms, he was both a compiler, like Ptolemy, and an innovator. Writings that carry his name comprise a huge body of literature – the total Galenic corpus has been estimated at 600 individual works. As with Hippocrates, however, it is impossible to determine in any final sense how much of this he actually authored. That he was prolific seems fairly certain. It is said that he had dozens of scribes taking down his words on any given day. True or not, the works given his name had an enormous impact starting in early Byzantium and, through translation, Islam and then, via translation again, in 12th–17th century Europe. Along with Ptolemy and Aristotle, Galen must be considered a massive presence in the history of western and near eastern scientific cultures.

Alchemy: early chemical ideas

At one time derided by scholars as a realm of superstition and greed, alchemy has more recently become a subject of detailed historical study, due in large part to its role as a forerunner of modern chemistry. Some historians now claim alchemy as a kind of proto-science, since it brought together empirical information, experimental methods, and theories about matter and transformation. Empirical information came mainly from the crafts of metallurgy and dyeing. Both involved extraction of substances from their natural material, then their purification, and their alteration into some kind of useful product.

The aims of alchemy, though, were both material and spiritual. These mirrored each other: discovering the process by which base, or "low," substances like lead could be changed into "higher," noble ones, like gold and silver, put one in touch with essential forces able to rejuvenate life and cure disease. At the most elevated level, such forces would be capable of liberating the human soul from its original sinful state of mortality and suffering into a more pure one of longevity and enlightenment. It is in part for this reason that men as brilliant as Isaac Newton spent much time studying alchemical writings. New scholarship has suggested that such ideas aided Newton in imagining the prevalence of invisible forces at work in the universe.

Alchemy was practiced by priest-craftsmen, possibly as early as the 6th century B.C. It was directly linked to a literature surrounding Hermes Trimesmegisti ("Thrice-Great Hermes"), a reputed Egyptian prince of the 2nd millennium B.C. but possibly a mixed god from the Greek Hermes and the Egyptian Thoth. Greek thinkers as early as Pythagoras seem to have had contact with alchemical ideas. But the true blossoming of actual practice came later, in Alexandria between the 3rd century B.C. to the 1st century C.E., encompassing, therefore, most of the Roman era. By this time, alchemy had been combined with the theory of the four fundamental elements and their properties, first fully elaborated by Empedocles (ca. 500–430 B.C.) and later embraced by Aristotle and the great majority of Geek scientific thinkers.

A competing theory related to the nature of matter was atomism, introduced by Democritus (460–370 B.C.). This is not the modern atomic theory of matter, though it somewhat resembles it. Nor is it the same as the idea of atom-like particles in Indian philosophy and medicine (see Chapter 4). Democritus proposed that all things consisted of tiny, indivisible, and indestructible particles, always moving and separated by void. All things emerge as transient phenomena from the motions and amalgamations of atoms. All is mechanism and necessity, with no divine hand anywhere and, ultimately, no chance for improving the human condition. Thus atomism – for example, as expressed by the Greek philosopher Epicurus and, in more eloquent fashion, the Roman poet Lucretius in his famous work *De Rerum Natura* ("On the Nature of the Universe") – stood directly against alchemy, as it did against all forms of divinity. The basic Epicurean ideas of atomism were followed, to a significant degree, in Rome but not in the Greek-speaking world of the eastern Mediterranean, where the theory of the four elements held sway.

Alchemical transformation did not only involve metals. It also concerned medicines, paints, dyes, and more. Among dyes, for example, it was the famous deep purple preferred by royalty throughout the region that represented the highest, noblest hue. As for what we would call laboratory work, physicians and pharmacists were leaders: they chose specific substances from stones and plants, ground or pulverized them, mixed them in formulaic amounts, heated and purified them, and experimented with improving them and with finding and testing new materials.

A pause for Plato: the idea of theory

Plato had a major impact on Greek science and its idea of "theory." Today, this word signifies a system of knowledge that defines the core of a particular field. Since the term came from the Greeks, we might ask what they meant by it.

The word *theoria* in ancient Greek refers to "rational contemplation," logical thought. Plato puts it forward in the *Republic*, his discussion of the ideal state. In Book VII, where he talks about education and knowledge, he introduces his famous allegory of the cave. Prisoners chained in a dark cavern live without sunlight, seeing only shadows on the wall in front of them cast by statues moved about in firelight behind them. One of the prisoners is freed: he turns around and realizes the shadows are only copies of another reality. But then, as he walks out of the cave, he sees that this too is an illusion. The real world is lit not by fire but by the Sun, source of all that is noble and perfect.

What does the tale say about science? This: the world we see and experience is only an appearance and probing it is not to be done for its own sake but for a moral purpose – to make contact with the highest reality, *the good*, the state of virtue taught by nature's perfection. This is where *theoria* comes into play.

Book VII of the *Republic* goes on to discuss geometry, astronomy, and music. Socrates (Plato's alter ego) implies that what we see in the night sky, our observations of planets and stars, are equivalent to what the freed prisoner sees when he turns and looks at the fire and the people manipulating the statues. Socrates says:

> The starry heaven which we behold is wrought upon a visible ground, and therefore although the fairest and most perfect of visible things, must be deemed inferior far to the true motions of absolute swiftness and absolute slowness. . . . Now, these are to be apprehended by reason and intelligence, but not by sight.

It is "absurd," Socrates insists, to spend so much effort documenting what is merely visible. This belittles "the natural gift of reason." It is "when a person . . . without any assistance of sense, perseveres until by pure intelligence he arrives at the perception of the absolute good, [that] he at last finds . . . this power of elevating the highest principle in the soul to the contemplation of that which is best in existence."

Such is the endpoint of *theoria*. Theoreticians, then, become the highest kind of thinker. With reason alone, they pierce to the heart of every scientific matter and reveal what is most needed, the beautiful and pure forms of order behind appearances.

Contemplate the modern image of Newton or Einstein. They are geniuses who went beyond all veils to uncover the final laws of existence. Can they also reveal to us something of "the absolute good"? Why was Einstein's brain removed within just seven hours of his death in 1955, then preserved ever after for a variety of scientific studies and experiments? Slides bearing pieces of this sacred substance now exist in laboratories around the world. Perhaps something of Plato's scientific morality haunts the present.

Aristotle: the great encyclopedist

As already said, the scale of his impact makes Aristotle the most influential scientific thinker of all time. The total number of writings given to him is large (150 books at least), diverse, and likely exaggerated. Most are known from manuscripts a thousand years or more removed from the lifetime of the author. They are in Greek, Arabic, and Latin, with the Greek versions native to 9th and 10th century Byzantium.

The textual community of Aristotle treats what we would recognize today as physics, astronomy, geology, biology, botany, zoology, meteorology, agriculture, music, linguistics, rhetoric, political theory, and philosophy. This qualifies as the first great encyclopedist, a teacher who tried to embrace the whole of human knowledge.

What follows, then, will concentrate on a selection of topics. It is crucial to begin with Aristotle's rejection of Plato – meaning, his denial that visible reality is only a mirage and that the true objects of knowledge are ideal forms that exist behind appearances. For Aristotle, the world we perceive with our senses is the real world; what matters is to study its phenomena and discover their causes. There is no void; total emptiness is impossible, as nature "abhors a vacuum." Today, we would agree, noting that space is filled with energy, dark matter, gravitational waves/particles, and so forth.

Aristotle's view must have seemed like common sense to a great many. The world we see, smell, and bump into *is* real and has an order, expressed in repeated events. To understand it, we need to carefully observe things many times – we can't grasp the process of flowing water until we visit many rivers and streams and closely note its behavior as it moves over rocks, carries sand and mud, and enters a lake or the sea. This all sounds quite modern. But Aristotle never recommended any kind of experiments and probably would have been against them. Why? Because they create artificial conditions and so would yield misleading results.

Aristotle saw moral purpose in nature too, envisioning a Great Chain of Being. This began at the bottom with inorganic substances and progressed upward to living things, plants, then animals, and finally humans at the top, capable of rational thought. The Great Chain was adopted by Christian thought, which added its own links (e.g. angels and God, above man) and was viewed as the essence of God's plan, an idea that lasted even into the 18th century.

Also appealing to later, monotheistic cultures, Aristotle declared the cosmos was infinite. He divided the universe between an upper celestial realm, perfect and unchanging, filled with aether, and a lower, sub-lunar domain, where change was constant. Thus, none of the other planets, except some parts of the Moon (which combined celestial and earthly substance) had volcanoes or water or life. The Earth, in other words, was magnificently unique. Though static at the cosmic center, it was nonetheless the domain of ceaseless transformation. For instance, due to their essential nature, air and fire rose from the surface into the atmosphere, creating many effects, including comets and meteors. Water and earth, by their own essence, sank down to form the land and sea, which influenced each other in a variety of cyclical changes.

In *Meteorologia*, Aristotle exhibits his characteristic reasoning with regard to the Earth, its oceans, winds, and earthquakes, among other phenomena. He begins each discussion by taking up prevailing ideas, rejecting (usually) or accepting (rarely) them on the basis of known facts, observations, and logic, before offering his own explanation. Here he reasons why the ocean is salty:

> The Earth is surrounded by water. . . . Now the Sun, moving as it does, sets up processes of change and becoming and decay, and by its agency the finest and sweetest [i.e. lightest] water is every day carried up and is turned into vapor and rises to the upper region, where it is condensed again by the cold and so returns to the Earth. This, as we have said before, is the regular course of nature. Hence all my predecessors who supposed that the Sun was nourished by moisture are absurdly mistaken.

The light, "sweet" water is "all of it drawn up; the salt water is heavy and remains behind."

Earthquakes, meanwhile, were caused by winds moving through tortuous passages within the Earth. The winds sometimes break through the surface and hurl "live cinders and ashes," as seen in a number of islands in the Aegean. It is an explanation that can seem fanciful, until we remember the roaring sounds that strong winds and quakes make and also that in this region earthquakes are often associated with volcanic eruptions, which throw out gases and particles in swirling masses of air. As for causes, Aristotle deduces these in the evaporation of subterranean waters. He relies, therefore, entirely on physical, material explanations.

Meteorologia was highly accurate in some areas. It observes that a severe quake sets loose a swarm of sizable aftershocks that can be felt up to 40 days or more, with smaller events perceptible even two years later. Most impressive, however, is the view shown by the quote given at the beginning of this chapter. Such is the essence of geologic time: it is immense, even inconceivable in human terms, so that most processes that have formed the Earth cannot be directly observed.

Aristotle here, in a few lines, describes a core element in the modern understanding of the Earth, one that Charles Darwin also used to support his theory of natural selection.

Despite many ingenious hypotheses, Aristotle's deductive logic led to some unfortunate conclusions. With time, the enormous authority he gained made such explanations real barriers to more exploratory science. One of these was his idea that each object, living or not, had a distinct "final essence" or "nature" that determined its reality. For example, it is in the nature of the seed to germinate and grow; it sprouts because its nature compels it to. Similarly, minerals begin from crystals that then propagate and mature into veins in the Earth. For motion, there is a "natural" movement for a particular object, whether bird or projectile, that ends when the object arrives at its "natural" place. Such belief in final causes helped to dissuade interest from further questioning (*how* does the seed actually germinate?). It also gave privilege to other simplistic notions. Aristotle stated, for instance, that natural motion depends on weight: if two balls fall from a height, the ball that weighs twice as much will travel twice as fast and hit the ground in half the time. Such was the kind of "common sense" conclusion to which Aristotelian logic could lead. We can begin to imagine, with so much authority behind it, why it was so difficult for many scholars to accept Galileo's famous experiment of the two balls dropped from the Tower of Pisa.

We should, however, examine one area of Aristotle's work that proved of lasting credibility. In *History of Animals* and *On the Parts of Animals* there is on display an excellent observing eye for detail and a larger sense of purpose. These aspects we can both see in Book I of *History of Animals*: "Some animals at first live in water, and by and by change their shape and live out of water, as is the case with river worms, for out of these the gadfly develops. . . . Other creatures adhere at one time to an object and detach themselves from it at other times, as is the case with a species of the so-called sea-nettle; for some of these creatures seek their food in the night-time loose and unattached." He then discusses the importance of animal classification, based on various properties: blood/bloodless, feathered, scaled, producing eggs versus giving birth to living young. Such are the kinds of broad distinctions that remain in use even today.

How to sum up Aristotle's importance? A brief survey like this can barely suggest the immense attraction his ideas commanded for so long. A principal reason, as scholars have often said, is that the Aristotelian corpus presented a fairly unified, consistent vision of the universe and everything in it – a vision in which everything has place, purpose, and meaning. The order of the world was revealed, not in arcane or purely mathematical terms, but in ideas and perceptions that accorded well with daily experience. Many of the most perplexing things – sublime and terrible events like storms and volcanic eruptions, the origins of lakes and rivers, the reason tiny seeds can grow into great trees – here seem unraveled. And for those phenomena that Aristotle somehow didn't explain, he provided a method for others to do so.

This method was simplistic, to be sure. It stressed the powers of reason and logic to derive final causes on the basis of a relatively few observations. There was no real place for experiment, for documentation (data, in modern terms), or for detailed analysis of how specific processes actually worked. Yet it would be entirely wrong to heap criticism on the Aristotle corpus for these reasons. Any negative impacts of Aristotelian thought in Islam and Europe were due to the excessive reverence granted this corpus so many centuries later.

Greek mathematics

As is the case with Greek science generally, our knowledge of mathematical thought is taken from secondary sources. We have the names of dozens of Greek mathematicians but not a single manuscript touched by any of their hands. Still, it is reasonable to assume that a good deal of the original material remains intact, given its great influence and, therefore, perceived importance. What we have suggests several major points. These can be summarized as follows:

1 The majority of early Greek mathematics came from Egyptian and Babylonian/Assyrian thought, meaning it was largely arithmetic.
2 Like other ancient peoples, the Greeks saw in mathematics a means to discover and make contact with the fundamental order of the universe.
3 The first great mathematicians are believed to be Thales and Pythagoras, though their contributions are known only from anecdotal comments and third-hand biographies, such as those by Diogenes Laertius, Iamblichus, and Porphyry.
4 Greek mathematicians, especially from the 5th century on, made profound innovations in a number of areas. Above all, they either introduced or systematized the use of proof, using theorems and step-wise demonstration. This gave mathematicians great power to analyze spatial phenomena as a source of real knowledge.
5 Geometry (both planar and spherical) was something the Greeks developed to a very high degree, in large part because of its role in astronomy. Indeed, geometric and astronomical thought progressed together.
6 Key texts in advancing Greek mathematics seem to have been written by a small handful of thinkers who lived a fairly brief period: Euclid (flourished around 300 B.C.), Archimedes (ca. 287–212 B.C.), Apollonius of Perga (ca. 262–190 B.C.), and Hipparchus, (ca. 190–120 B.C.).
7 Like the rest of Greek science, we know of these mathematical advances mainly through their translation into Arabic, adoption and expansion by Islamic mathematicians, and then the subsequent translation into Latin of these Arabic versions, as well as some late-stage texts in Byzantine Greek.

A few words should first be said about the numbering systems devised and used by the Greeks. In fact, two systems were used – an earlier one very similar to that in Egypt and a later, alphabetic system that was more condensed and positional but lacked a zero and other features compared to the modern base-10 Hindu numeral system.

The first Greek numbers were acrophonic, meaning that each number symbol was simply the first letter of the name for that number. The system was in base 10; there were symbols for 1–10 and for 100, 1000, and 10,000. Yet it was not used in a base-10 way. Writing numbers was additive, like Roman numerals, so that symbols piled up rapidly, e.g. the figure 49 required as many as nine numerals: four 10s, one 5, and 4 ones. Another complexity was that the actual drawing of each numeral was not standardized and could vary significantly between different city-states.

The second system, developed around 450 B.C. and in widespread use a century later, was based on the Greek alphabet, with each letter assigned to a number. This included 1–10; 20–100 by tens; and 200–900 by hundreds; thus 27 numbers in all. It allowed for much more concise writing of numbers, in positional form. For numbers larger than 900, small marks (similar to an apostrophe) would be used above lower numerals, e.g. α' and β' would represent 1,000 and 2,000, respectively. The largest numbers the system was capable of dealing with were defined by the "myriad" for 10,000, so that a "myriad myriad," or 100,000,000, was as far as the system could go. The brilliant Archimedes extended the system in order to calculate the number of sand grains needed to fill the universe. First designating all numbers up to a "myriad myriad" as the "first order," he then assigned new orders, by successive multiples of "myriad myriad" up to 100 million to the 100 millionth power, i.e. in scientific notation, $(1 \times 10^8)^{100,000,000}$.

Euclid, Archimedes, Apollonius

Though he wrote one of the most influential books in all of mathematical history, scholars have been unable to determine even the basic facts of Euclid's birth and death. Some ancient authors called him "Euclid of Alexandria," suggesting an important association with that city. Others do not use this title. Either way, *Elements* was an extraordinary work. Though not entirely novel in content – many of the problems in the book and much of its theory were already known – it was hugely innovative in how it organized its material, giving it a logical order and introducing the rigor of mathematical proof. So important was this last factor that it remains at the core of a great deal of mathematical effort and teaching today.

As suggested by its title, *Elements* was written as a textbook. In the versions we have, Book 1 begins with definitions, axioms, and postulates, then proceeds to give proofs for 50 different "propositions" about triangles, parallels, and areas (e.g. "Proposition 1: On a given finite straight line, to construct an equilateral triangle."). Books 2–6 continue with propositions about other shapes: rectilinear figures, circles, inscribed and circumscribed figures, and the theory of proportions. Then, in Books 7–10, the author moves into number theory and in the last three books (11–13) to solid geometry and measurement. There are many diagrams, yet we do not know what the drawings were actually like in the original, how large or explicit they might have been, or how they were labeled. It is clear from an examination of different manuscripts, starting with fragments as old as about 100 C.E. (Figure 5.10), then leaping to the oldest complete version dated 888 C.E., that

Figure 5.10 One of the oldest known fragments showing a diagram from Euclid's *Elements*, dated 75–125 C.E. It is part of a papyrus scroll, possibly used for teaching or studying. The crude diagram, without any labeling, suggests functional use, perhaps for private study. Discovered in 1897 in middle Egypt, at the ancient town of Oxyrhyncus, roughly 110 miles south of Cairo, it was part of a huge pile of material thrown away (in an ancient dump site) in Roman times. Specifically, the fragment contains part of Proposition 5 from Book 2 of *Elements*.

these drawings became larger and more prominent with time, implying that their use in actual classrooms became more important with time.

Archimedes, meanwhile, is known to have been born about 287 B.C. in Syracuse, on Sicily. His father was a well-known astronomer and likely introduced him to many scientific subjects. Archimedes seems to have studied mathematics in Alexandria, under Euclid's best students. His death in 212 B.C., reputedly at the hands of an ignorant Roman soldier, came during a Roman attack on Syracuse. This was a great loss, felt deeply by the Roman general Marcellus himself, who had ordered that Archimedes be spared so that his "gifts" could serve Rome herself.

What were these gifts? Today he would most likely be called a mathematician and applied physicist. We do have a fair idea of what his talents were, because of the many things written about him. He is one of the very few Greek thinkers to have extended mathematics into many realms beyond astronomy, to have discovered fundamental principles of physics, and also to have invented a wide range of machines, including a small working model of the solar system and a series of defensive military devices of major scale. He was known to be a master problem solver and constantly challenged himself by conceiving new problems to work on, some of a practical nature but many purely theoretical, even playful.

For non-mathematicians, Archimedes is legendary for the mechanical devices he conceived to protect his native city. That it would be attacked he was certain, due to the strategic position of Syracuse between the warring empires of Rome and Carthage. Accounts written by the Greek historian Polybius (200–118 B.C.), as well as by the Romans themselves, speak admiringly of how Archimedes' machines held a siege by both land and sea at bay for as long as eight months. Uniquely sized catapults and ballistae rained down stones and large darts, able to crush Roman protective blinds and battering rams on land and to drive off ships that approached from a distance. When the ships tried to attack at night, by silent approach, the Syracusans, using ropes and pulleys, extended out from the city walls long chutes from which stones and blocks of lead were dropped, smashing the attack once more. Most ingenious of all was a so-called "great claw" of iron lowered from the walls by another pulley and beam system (Figure 5.11). Once finding a grip on the prow of any ship, this giant grappling hook would lift the entire ship out of the water to a near vertical position, hurling all its sailors overboard, then being released so the ship crashed downward on its side or wholly upside down. Such spectacular defenses utterly baffled and dispirited the Romans. They were able to capture the city only after guards fell asleep in one of the towers.

What, then, of Archimedes' contributions to mathematics? His major efforts were in geometry. He discovered how to find the volume of a sphere and determined the value of π to five places. He also employed the "method of exhaustion" – that is, the inscribing of polygons of progressively more sides – to find the areas of a variety of curved shapes, including a circle, ellipse, and segment of a parabola, as well as the volume of a sphere. He discovered a number of areal and volumetric

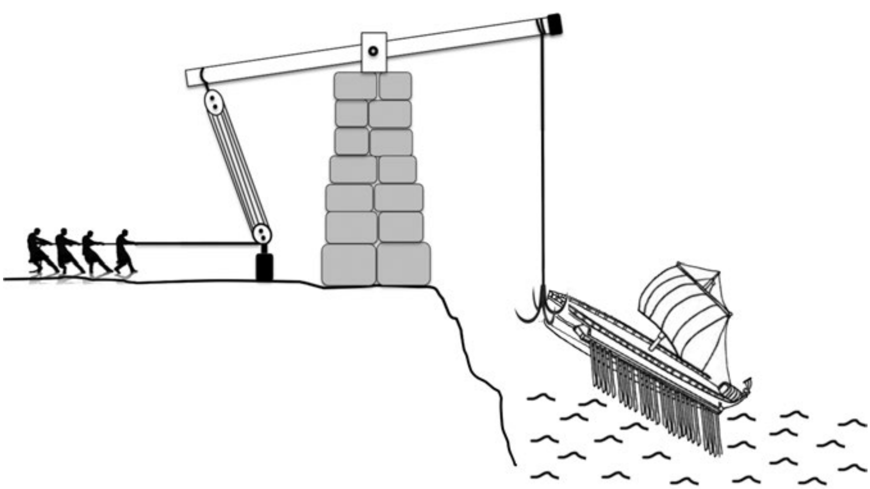

Figure 5.11 Drawing to illustrate Archimedes' "claw" invention, using a pulley system and grappling hook to lift attacking ships out of the sea.

relations between geometric figures. Examples here would include: 1) the surface area of a sphere is 2/3 that of a cylinder whose height and diameter are the same as the diameter of the sphere; and 2) the volume of a sphere is four times that of a cone whose base and height are equal to the sphere's radius. Such examples indicate the experimental, exploratory nature of Archimedes' mind.

A few of his more practical discoveries suggest this as well. He found, for instance, that the maximum weight a lever can raise is a direct function of the lever's length from the fulcrum. "Give me a place to stand, and I will move the Earth," he is reputed to have said – though this place would obviously have to be well out in space. Another story has it that he claimed the ability to lift the Earth if given enough pulleys, which he had modified to a highly advanced level by his understanding of force distribution. In this case, Syracuse's king is said to have challenged him with the task of moving a great ship, fully loaded with passengers and cargo, up a ramp, a task that Archimedes deftly achieved with a multi-pulley system that allowed he alone to pull a single rope and bit by bit draw the great ship easily along. This same basic system Archimedes applied to defense of the city, as just noted.

Even more well known is Archimedes' discovery of the principle of displacement and buoyancy. In this case, he was given the task by his friend, the king of Syracuse, to determine whether a new crown made for him was actually of pure gold as advertised or of a cheaper mixture. The story runs that Archimedes puzzled over the problem until one day, when getting into an over-filled bath, he discerned that his body caused the bath to overflow, thus to displace a specific volume and weight of water. Such gave him the answer to his problem, and he ran naked through the streets of his home city shouting "Eureka!" which means, "I have found it!" What he then did, according to the Roman author Vitruvius (1st c. C.E.), was to take a small block of pure gold, weighing precisely the same as the crown, place it in a bowl, and fill the bowl to the very brim. He next removed the block, letting all water drip off it back into the bowl, and finally lowered the crown into the bowl to see if it caused the water to rise to exactly the same level or, if some silver was mixed in, causing it to overflow, which is just what happened.

In one brief tract, *The Sand Reckoner*, addressed to the king, Archimedes tells a kind of mathematical story of his own. He begins by noting that there are those who "think that the number of the sand is infinite," meaning the amount of sand on the surface of the Earth. And so they could never conceive of a number so large as to describe the number of sand grains required to fill the entire Earth, up to the height of the highest mountains. But Archimedes says he can calculate the amount of sand it would take to fill the entire universe – even if it were as large as Aristarchus of Samos says it is, i.e. many times the accepted size. He then determines that the diameter of the spherical universe is somewhat less than 10,000 Earth diameters. But before he can fill this with sand, he must invent a whole set of new numbers far larger than any the Greeks had ever used. So, he develops this new system, in a logical, step-wise fashion, and then, using the poppy seed as analogous to a sand grain in size, builds from a "finger-breadth" to 10 billion stadia, the diameter of the universe. The process is smooth, intricate in its geometric portion, but entirely rational in its progressive movement from the visible to the spectacularly huge.

But why is such an exercise worthwhile? How can knowing the number of sand grains required to fill the sphere of the universe – Archimedes' final figure amounted to 8×10^{63} – be important? The author himself ends this brief writing (~10 pages) by saying to his addressed reader, King Gelon, that "it would be not inappropriate for your consideration," because he too is "conversant" with the vast scale of planetary distances and the universe itself. We may guess, then, that Archimedes is appealing to something more than a sense of spectacle or play. He has shown, instead, that mathematics indeed has great power – power enough to give human beings the ability to grasp and even imaginatively manipulate the cosmos. No less, *The Sand Reckoner* shows that it requires someone of considerable ingenuity and inventiveness to make this so. Kings, in short, have great need of (and should always support) mathematicians of the first order.

Apollonius of Perga, a contemporary of Archimedes and also taught by students of Euclid, was himself known as "The Great Geometer." Once again, we

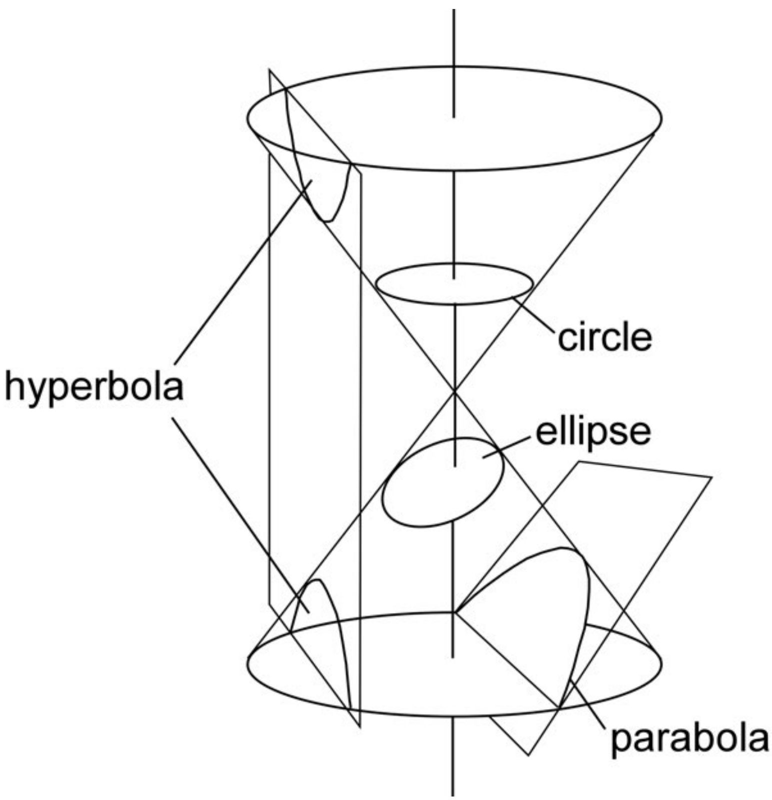

Figure 5.12 Conic sections, as defined by Apollonius of Perga.

have very little solid biographical information. Like so many other Greek scientists and mathematicians, he grew up in Asia Minor, meaning the Ionian cities along the coast in what is now westernmost Turkey. It seems fairly certain, since his teachers were among Euclid's followers, that he studied in Alexandria at some early point.

In the most famous work attributed to him, *On Conics*, he introduced such vocabulary as ellipse, parabola, and hyperbola, as well as many complex geometric proofs and relations involving these figures. Conic sections, as described by Apollonius and predecessors, are shown in Figure 5.12. They represent the curves created when a plane intersects a cone at various angles. Apollonius systematized and greatly extended knowledge about them. *On Conics* shows that he took geometry in new directions, as well as extending Euclid's work in profitable ways.

As we might surmise, Apollonius' work proved enormously valuable for later study of celestial objects and motions, including that by Kepler and Galileo, as well as Newton. Indeed, most of the scientists and mathematicians of the 17th century in Europe felt the need to be conversant with this work. *Conics* follows a pattern set by Aristotle: it begins by surveying and summarizing previous knowledge in this area (Books I-IV) before presenting its own propositions, theorems, and proofs (V-VII). We might recognize this pattern as familiar.

According to later writers, Roman, Greek, and Muslim, who wrote commentaries on Apollonius' work, he composed as many as a dozen or more treatises in all. Most of these, it appears, dealt with purely mathematical problems of ratios, areas, inscribed polygons, and so on. Much of this work was translated into Arabic and had a strong impact on Islamic mathematicians.

Concluding words

The alert reader of this chapter will have noticed something that isn't often mentioned about Greek science. Most of its greatest minds did not come from mainland Greece but from the cities and islands of Asia Minor. These were the cities and islands of Miletus, Ephesus, Mytilene, Cnidus, Nicaea, Perga, Samos, Kos, Chios, and Rhodes, to mention the most important. Moreover, most of the thinkers we have discussed were travelers, active seekers of knowledge from different sources and traditions in the eastern Mediterranean region. Our attentive reader will by now suspect why this was significant.

Beginning in the 19th century, western historians routinely held that all true science began with the Greeks, starting in the 6th century B.C. Central to this interpretation has been the idea that pretty much all earlier understanding of nature was deeply stained by religious supernaturalism. The human mind in earlier societies could be described, in Carl Sagan's memorable phrase, as "a demon-haunted world." It was the Greeks who arrived, finally, to clear away the ghosts and spirits and begin the first rational studies of nature.

Today, historians know this to be wrong. As we have shown in previous chapters, a great deal of systematic observation, experimentation, and rational study of natural phenomena took place in Egypt, Mesopotamia, and India. It also happened in China, as we will soon see. Indeed, without such effort and its successes none of these early societies could have ever built themselves into great civilizations. The enormous prestige granted the Greeks, their importance to medieval European science and to the Scientific Revolution, was neither false nor undeserved. Greek achievements in science were immense, by any measure. But they were neither wholly unique nor without considerable debt to scientific cultures that had spent millennia developing reliable knowledge about the physical world.

The truth is that the Greeks came late in the world of ancient science. Moreover, they were not the product of spontaneous generation. As we've said, those such as Hipparchus and Ptolemy had many centuries of Egyptian and Babylonian, and perhaps even some of Indian, astronomy and mathematics to draw upon. There is a great deal left for historians to study and reveal in the flows of knowledge that took place. But understanding that these men benefited greatly from earlier thought takes nothing at all away from them. Nor can the achievement of Greek science, the profound step forward it represents, be said to erase or dilute any of the major advances that went before. It is perhaps worth remembering that when the Mycenaeans and the later Greeks thought of the wider world, and when they wrote about it and made maps of it, it was toward the south and the east that they turned.

Note

1 There is a short text, dating from the 4th century B.C., that describes a poetic contest between these two (Hesiod wins). *The Contest of Homer and Hesiod* is in all probability a work of fiction, but it indirectly supports the idea that the two poets lived about the same time.

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6 Science in China

The wages of order and invention

> Eastward his empire extended to the sea. . . . He urged the people to act in accordance with the celestial and terrestrial arrangements. . . He also prepared a record of the movements of the sun, moon, and stars; the flow of the tides; and the properties of clay, stones, metals, and gems. He devoted much careful attention to these things, and . . . to ascertaining how fire, water, wood, and other elements could be used.
>
> *Shiji ("Annals of the Five Emperors")*, Sima Qian

Marco Polo was a Venetian merchant who journeyed to China in 1271, returning 26 years later. For over 17 of those years, he lived, traveled, and worked in China, at times serving Kublai Khan, grandson of Genghis. Much of what he saw and learned was recorded in a book, *Description of the World* (today known as *Travels of Marco Polo*), published around 1300. It is a volume of some historical significance: there is evidence that it had an impact on the imagination of another Italian explorer, Christopher Columbus.

Or so it has been claimed. But what if Marco Polo was a liar? Traders, after all, are notorious tellers of tales, both tall and small. Polo did go to the eastern end of the Black Sea; this we know for sure. But there he could well have collected a bag of stories from those arriving on the Silk Road with their own narrative curiosities. Some scholars have decided that Marco Polo was indeed a writer of fiction. How can we decide the matter?

By details, of course. As it happens, historians have discovered the particulars of subjects in the book that are nowhere else recorded but in Chinese sources. Such topics would not be known to idle, short-term travelers. They were neither "sights" nor spectacles but ordinary phenomena. One of them involves the production of salt.

Chapter 38 of *Description of the World* tells us that in Yunnan Province "there are salt springs, whose waters are boiled in small pans," creating a paste. This "is formed into [little] cakes . . . placed upon hot tiles, near a fire, in order to dry and harden." The final product, perhaps an inch or so in diameter, is not for food. Instead, it is impressed with the stamp of the Great Khan and then used as money. Meanwhile, in Chapter 50, we find this fascinating passage about the area near "Chang-du":

> In the country is found a briny earth; upon this, when laid in large heaps, they pour water, which in its passage through the mass imbibes the particles

> of salt, and is then collected in channels, from whence it is conveyed to very wide pans, not more than four inches in depth. In these, it is well boiled, and then left to crystallize. The salt thus made is white and good, and is exported to various parts of the whole nation.

What do these two methods of salt-making tell us? First, that there was considerable knowledge of geologic conditions, including groundwater as well as rock and soil types. Second, that much experimenting had been done to find the most efficient ways to collect the relevant raw material, heat it, and maximize the rate and quality of salt crystallization. If Marco Polo had the eye of a merchant, it would appear his time in China greatly expanded both his curiosity and his appreciation for science-based technologies.

Background

China is the last of the great river valley civilizations in the eastern hemisphere. Its name was known to ancient India as Cīnah (Cheena) in the Sanskrit language. Medieval Europe knew the country as Cathay. Only in 1516 did it appear as "the very great kingdom of China" in the famous travel journal of the Portuguese explorer Duarte Barbosa. China's cities, writing system, and scientific culture all matured later than the other river valley civilizations. By the 2nd century B.C., when Egypt and Mesopotamia were centuries past their prime, China was a flourishing, politically unified state, whose science and technology were perhaps the most advanced in the world.

From the beginning, geography, climate, and ecology played no less a role here than in other civilizations. Major rivers flow eastward from the Tibetan Plateau, creating fertile floodplains in the eastern third of the country, especially along the Yellow River to the north and the Yangtze to the south. The broad lowlands of these two great rivers make up the North China Plain, where most early settlement developed (Figure 6.1). Agriculture began with the cultivating of wild plants as early as 11,000 B.C., while domestication in permanent settlements appeared by 7500 B.C. This timing, which parallels the era of agricultural expansion in Egypt, Mesopotamia, and the Indus Valley, is associated with the Holocene Thermal Maximum. It suggests early agriculture matured when the climate was most friendly, so adaptations were needed later on, as conditions cooled and dried.

But while the valleys of the Yellow and Yangtze were mild and fertile, they had other factors less welcoming. Most formidable was flooding, which could occur on a hugely destructive scale. This was especially true of the Yellow River, known both as the "mother of China" and "China's sorrow." Flooding of the Yellow was particularly dangerous for three reasons. First, spring and early summer meltwater from the Tibetan Plateau swells the river's discharge up to 16 times. Second, being extremely flat, the North China Plain allowed floodwaters to spread for great distances and the river to change course dramatically. Third, the Yellow has the highest sediment load of any river in the world, due to its course through the Loess Plateau, an erodible province of very fine, wind-blown silt. Millions of tons of this silt give the water its distinctive color but also an increased density that raises its destructive force. Together, these three factors meant the deaths over time of millions of people.

Natural borders, meanwhile, and sheer distance separated China from other early valley civilizations. The kind of bustling commerce between the Indus and Sumer cultures in the fourth and third millennia B.C. didn't come to China until much later. Such trade did develop, however, within China itself (Figure 6.1), a pattern of much importance thereafter.

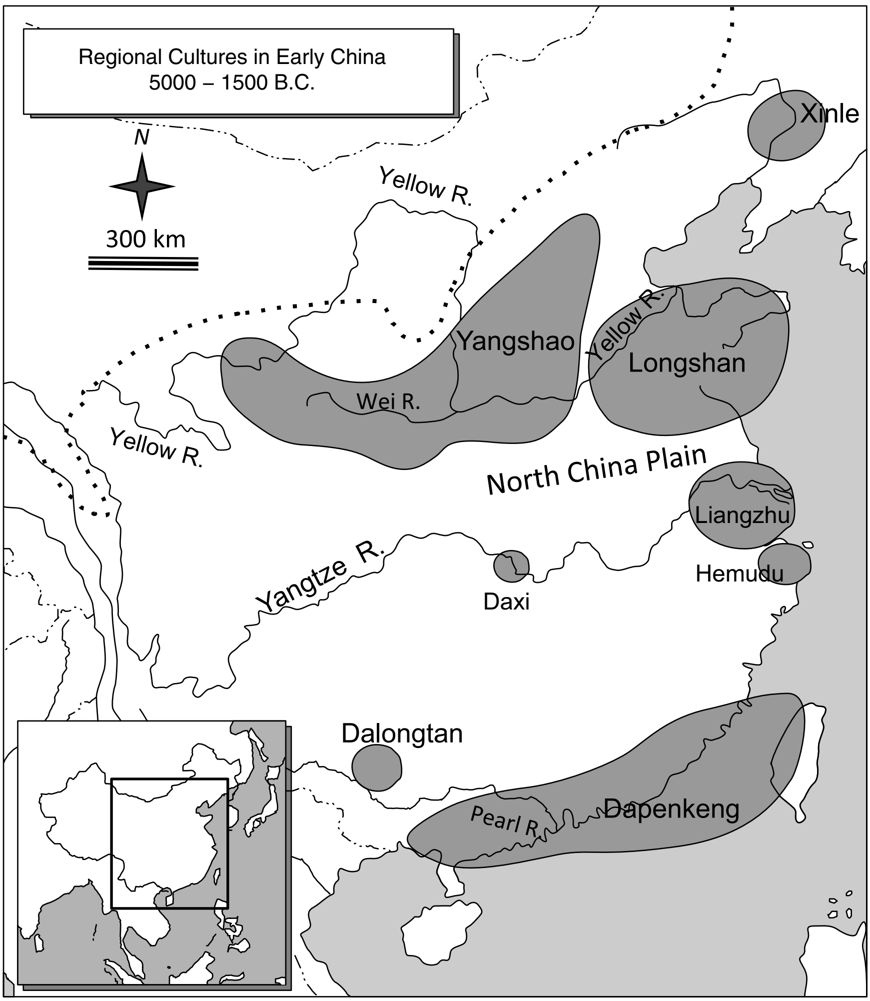

Figure 6.1 Map of major Neolithic cultures in China, 5000–1500 B.C. Also shown are the Yellow and Yangtze rivers and the westward limit of precipitation down to 15 inches (380 mm) per year (dotted line).

The first village networks date from around 5000 B.C. At this time, large portions of China were as much as 2°C (3.6°F) warmer and much wetter than today, with forests, grasslands, and lakes. Such mammals as elk, wolves, bears, lynx, elephants, and perhaps rhinoceros lived in parts of northern and eastern China. The presence of elephants and probably rhinos is confirmed by an abundance of ivory found at various Shang Dynasty (1600–1050 B.C.) sites and also the frequent depiction of these animals in bronzeware of the time. These animals were extinct by about 1000 B.C. This was due to a combination of drying climate, hunting, and an active ivory industry and trade, as well as demand for the presumed medicinal and protective (against evil) properties of powdered tusks.

Archeological study tells us that the era of city-states, with palaces at their center, differentiated social classes, slavery, and standing armies, was well developed by the 2nd millennium B.C. Consolidation of urban centers into a single large kingdom in eastern China occurred around 1600 B.C. under the Shang rulers. It is possible that an earlier dynasty, the Xia (2100–1600 B.C.), existed and, in fact, has long been part of Chinese historical lore. Yet it remains unconfirmed by hard evidence.

The vast number of artifacts recovered from the Shang capital, Anyang (Henan Province), includes elegant ceramics, intricate bronze works, expertly carved jade, and also oracle bones with the first writing (see Figure 6.2). These are works of an advanced culture, one that also practiced animal and even human sacrifice (burial of servants, officials with a king). The Shang were eventually defeated by armies

Figure 6.2 An example of an oracle bone (turtle plastron) inscribed with early forms of Chinese writing. An entire technology, based on precise knowledge of relevant materials, was involved in the preparation, process of inscription, and finishing of such bones.

of the Zhou (also: Chou), whose dynasty lasted from 1045 to 256 B.C. It was during the later stages of the Zhou era that many works of immense importance were written, including those by Confucius and Lao Tzu, creators of Confucianism and Taoism.

By this time, the use of chariots, similarities in objects like daggers, and motifs of decoration show there was regular contact with Central Asia, whose nomads were intermediaries between China and the Near East. Early contact with India had also begun, revealed by literary references, such as "cheena patta" (lit. "leaf from China," meaning Chinese silk) in the Indian epic *Mahabharata*. More frequent exchange came with the import of Buddhism in the 4th century B.C. Major trade along the Silk Road was established a century later, when the Qin and Han dynasties expanded the Chinese state. The spread of plants, animals, and traded goods, as well as the remains of wrecked ships, all prove that the Indian Ocean was acting as a kind of maritime Silk Road, with India itself as a supplier of native goods and a relay nexus between China and the Roman Empire for the silk trade.

Chinese recorded history is generally a tale of dynasties up to 1912, when the last emperor abdicated. For over two millennia, that is, China was an imperial state, ruled by an emperor and administered by a vast, powerful bureaucracy. An extremely demanding exam system, begun in the Han Dynasty and expanded under the Song (960–1279 C.E.), focused on classical Confucian texts and determined who might enter this elite civil service. It was a system to recruit the best minds – defined as the most learned in literature, philosophy, and ethics. Yet the "best minds" idea proved limited in important ways. Except for a few brief periods, it did not include mathematics or science. Nor did it fully work as a fair scheme. Children of officials were given special consideration, while wealthy families routinely had better training and coaching. Cheating became an art and an industry (miniature books were sold that could fit in a sleeve). Many creative minds failed the exam, including artists, poets, and the technically gifted.

Science was not overlooked by the government, however. Those skilled in astronomy/astrology and mathematics were employed in official calendar-making, for example, while engineers were seen as essential for projects in irrigation, flood control, and canal building. Scientists and engineers, broadly defined, were always part of imperial government. Indeed, in two particular eras, the Han and Song, government supported a flowering of intellectual activity that helped scientific culture make enormous strides. We know of this in some detail, since these were also periods of much writing and preservation of earlier written material.

This brings up a key point. As in India, scholars in China have kept alive entire traditions of learning from ancient times to the present. This includes essential works, such as the Five Classics, which record poetry, cosmology, social rites, historical (or semi-historical) information, and divination (*I Ching*). Unlike with Greece, therefore, we have a significant number of texts that date from even before the Christian era.

One final aspect about ancient China was its mixture of secular and religious aspects. People certainly believed in a divine order, as well as in spirits. The most ancient writings make plain the importance of sacrifice and oracles and the central role of ancestor worship. Yet Chinese society did not place human life in thrall to the divine. There was no priestly class, no pantheon of all-powerful deities. No divinity of the Sun or Moon strides across the pages of writings on the heavens. Humans mostly had the power to control their own destinies by the choices they made: bad kings who ignored the natural order lost their "mandate from heaven" (and, therefore, could be rightfully deposed), while good kings brought peace and bounty. Human capability was determined by self-cultivation and ethical behavior.

Chinese ideas about the physical world: a brief overview

These comments suggest we might look briefly at some basic ideas in ancient Chinese science. There is a challenge here. As the eminent Chinese scholar Benjamin Schwartz has stressed, our "words such as nature, reason, science . . . which are deeply encrusted with countless layers of meaning on our own past, meet Chinese terms such as *tao*, *yin-yang*, and *ch'i*, which have as complex a history of their own within the Chinese tradition."

Such ideas came to form something a system of nature interpretation during the first two imperial dynasties – the Qin (221–206 B.C.) and, especially, the Han (206 B.C.–220 C.E.). They are a fascinating mixture of religious, political, ethical, and technical concepts that were emphasized in different ways by different schools. Thus, no single philosophy of nature ruled. Instead, there were competing views, mostly rooted in the Five Classics, and based on several principles that dominated explanations of the physical universe.

One of these held that nature has an all-encompassing order, referred to as "heaven" and sometimes "god." Nature and humanity comprise "everything under heaven," with the emperor "the son of heaven." Spirits, especially of ancestors, have powerful influences; thus rituals and oracles are devoted to them. Yet spirits often respond to human behavior. Humans are responsible actors, and the primary concern is how life should be lived. The *Book of Documents*, one of the Five Classics, states there is a "Great Plan" in the cosmos. Good rulers accept this "mandate of heaven," which includes acquiring some knowledge about nature and its workings in order to protect and advance the well-being of the people.

Within this larger frame was the scheme of "the five agents" or *wu xing*. Written with the characters for "five" (*wu*) and "movement" or "behavior" (*xing*), these are often mistranslated as "five elements" and given a parallel to the Greek "four elements" (earth, air, fire, water). *Wu xing*, however, are not primordial substances; Chinese thought did not pursue this idea but focused instead on dynamic relationships and properties. The five *xing* include: water, fire, wood, metal, and earth (suggesting a Bronze Age agricultural setting), which refer to substances and conversions. *The Book of Documents* says the nature of water is to moisten and descend and to become salty; fire, to flame and ascend, to become bitter; wood, to be straight or curved, to become sour; metal, to yield and transform, to become tough and acrid; earth, to take seeds and produce crops, to generate sweetness. Later texts lay out aspects of nature correlated with each *xing*, e.g. fire is associated with red, south, summer;

Mars, blooming of plants, excitability; metal correlates with white, west, autumn; Venus, withering of plants, lack of will. Each *xing* has relationships of dominance with the others in an overall cycle: wood divides earth; earth absorbs water; water quenches fire; fire melts metal; metal chops wood. The total scheme, then, could characterize most phenomena and predict their behavior. Over time, it was applied to nearly every domain of knowledge. By late Han times, it had merged with two other concepts – *ch'i* and *yin-yang* – to yield a more expansive system of explanation, though without a single orthodoxy.

Ch'i (also *qi*) refers to the natural flow of energy in all things, similar to the Sanskrit term *prana*. Written with the character meaning "air" or "breath" (or "vapor"), it permeates and links together macrocosm and microcosm, so that changes in the planets, atmosphere, or seasons affect living things. Its circulation in the body utilizes special pathways, called meridians and channels, and involves a person's mental life as well as the physical body. A person's *ch'i* grows until they reach adulthood. By age 40, it has fallen by half; at 60, it is so reduced that, unless rejuvenating measures are taken, the person looks aged and fragile.

Yin-yang was also defined and applied variably but seems to date from even before Shang times. In earliest written material, *yin* and *yang* meant opposing yet complementary aspects – *yang* as brightness, the sunny south side of a mountain, *yin* as darkness and the shady north side. Such examples suggest an origin in the daily life of an agricultural, river-based society that did not use deities to explain phenomena. Taoist philosophy greatly expanded the use of *yin-yang*, linking it to: 1) the universal process of seeking balance or equilibrium; 2) a fabric of dualities observable in nature; and 3) interaction between the cosmic and human domains. In broad terms, *yin* applies to "softer" realities like femaleness, slowness, coolness, water, night, tranquility, while *yang* applies to "harder" aspects, such as maleness, speed, hotness, dryness, daytime, agitation. Imbalance comes from too much *yin* or *yang* for a given situation or object. All life, therefore, can be described as an unending search to find and maintain balance: "If one follows yin and yang, then life results; if one opposes them, then death results. If one follows them, then order results; if one opposes them, then disorder results," in the words of the *Book of Documents*. All of these prescriptions apply to human behavior and the political system as well.

Finally, we must mention the idea of the *tao*. In regard to nature, it can be simplified into an all-embracing unity that began with the origin of the universe. Written with the character for "way" or "road," the *tao* is never defined in ancient writings, only described, as in the famous *Tao Te Ching* by Lao Tzu. Taoism has a goal: to find ways by which one can make contact with the *tao* itself, the primal order. Taoists, interestingly, pursued empirical work with various substances to discover elixirs or potions that might achieve this and extend life. Chinese alchemy evolved from this tradition, which shares some aspects with Egyptian and Greek ideas.

Overall, the Chinese view of nature was utilitarian. Understanding the *wu xing* of a phenomena, as well as its *yin* and *yang* elements, dictated how it could be used for human benefit. This meant rivers could be changed in their course, mines and tunnels dug into mountains, forests leveled, land developed. Nature was neither fragile nor exhaustible. It was not specifically created for human use, but remained at all times available for this purpose.

Qin and Han Dynasties: from technology to science

If we may speak of an "axial age" for early Chinese scientific culture, it would begin in the later Warring States Period and reach a peak over the next four centuries, the time of the Qin and Han Dynasties. Such is when scientific culture was truly harnessed and given legitimacy through government policies and projects.

The Warring States Period came to an end when local kingdoms were forcibly brought under the rule of China's first emperor, Qin Shi Huang. Brief, brutal, and bloody, the Qin Dynasty (221–206 B.C.) lasted a mere 15 years yet established the first true Chinese state, vast in extent, diverse in people, unified in government. It sought to dismantle the existing feudal system and impose a highly centralized political structure, with a massive bureaucracy reaching into cities, towns, and rural areas. Inspired by a potent combination of centralizing ideas and mathematical vision, the new imperial administration divided the country into prefectures, districts, counties, and units, each governed by appointed magistrates and military commanders. Ruling families of the local kingdoms were ordered to live in the capital, Xianyang (Shaanxi Province), where hereditary titles were abolished. Walls built by six of the Warring States' kingdoms to hold back each other's attacks were torn down. A vast army was assembled to keep order and protect both the northern border and the trade routes with India and Central Asia, sources of new wealth.

Centralized control was thus a primary goal. To help achieve this, efforts were made to standardize key elements: bureaucratic procedure, legal codes, roads, time measurement, weights and measures, currency, and the writing system. Scientific knowledge did not advance much at this time, but technology was taken to new levels of scale. The political system allowed massive labor forces to be assembled for imperial projects. Meanwhile, the government took control of industries, such as mining, metalworking (in part), quarrying, wine-making, and salt extraction.

This was not enough. Legalism, as a guiding philosophy of government, was interpreted to mean conformity of thought, as well as behavior. Such came from Li Shi, the emperor's prime minister and chief advisor. As described in the *Shiji* ("Records of the Grand Historian"), a history of China written in Han times, Li Shi maintained the emperor was all-powerful and had the right "to utilize the empire for his own pleasure" without "torturing" his mind by worrying about his people.

Modern scholars consider the Warring States Period a foundational age of Chinese philosophy. Multiple centers of power and wealth helped support an open environment for philosophies of many kinds, an environment called the Hundred Schools of Thought. The Qin state had been the birthplace of Legalism, strongly opposed to Taoist and Confucian views. The Qin Dynasty brought a quick end to the Hundred Schools period. Li Si argued that diversity of thought led to criticism of the laws and thus of the emperor himself, whose power would decline. "Your servant suggests," Li Shi is recorded to have written,

> all books in the imperial archives, save the memoirs of Qin, be burned. All persons . . . in possession of the *Book of Songs* and *Book of Documents* and discourses of the hundred philosophers, should take them to the local governors [for burning]. Those who dare to talk to each other about [these books] should be executed. . . . Anyone using the past to criticize the present should, with all members of his family, be put to death.

The result was the infamous "burning of books and burying of scholars" episode. A great many copies of the Five Classics and a host of other works were destroyed, while some 460 prominent thinkers and writers were executed.

The emperor, however, did not censor everything. Li Shi advised that "books not to be destroyed will be those on medicine and pharmacy, divination . . . agriculture, and arboriculture." He thus "pardoned" books on scientific and technological subjects. Such works, that is, were too important to the practical vitality and economy of the empire. But this also meant their knowledge was utilitarian, not capable of being "dangerous," as were the domains of philosophy, literature, and ethics.

Of walls and warriors: Qin technology in the Great Wall and terra-cotta army

The Qin Dynasty is world famous for two spectacular feats of engineering: the "10,000 li" Great Wall and the emperor's tomb and terra-cotta army, located near the city of Xi'an, Shaanxi Province. Both projects, like Egypt's pyramids, demanded vast amounts of planning, labor, organization, natural and artificial materials, food, and water – the full technological resources of a state. Estimates of workers, including soldiers, slaves, prisoners, and conscripted locals, range to more than one million for the Great Wall and 700,000 for the emperor's tomb. Qin authorities were less interested in the welfare of their workforce than the Egyptians, however. Accounts suggest over 300,000 died building the Great Wall due to injury and lack of medical care.

The wall built at this time stretched for more than 5,000 km, from Pyonyang, North Korea, westward in a great arc to Lanzhou at the foot of the Qiling Mountains, Gansu Province, the entire northern border of the imperial state, as a defense against Xiongnu nomads. Where possible, it was made using stone blocks from the local country rock, mixed with wet earth and clay. In areas without rock, rammed earth – layers of sand, gravel, silt, and clay poured between wooden frames and pounded into firm, hard blocks – was used. Rammed earth, in fact, comprised the greater part of the wall as a whole.

As for the emperor's tomb, it forms an earth-covered mound at the center of a great necropolis. From subsurface maps based on ground-penetrating radar, the mound includes a full-scale palace, whose center is the actual grave chamber. The palace sits within a site of about 10 square kilometers defined by an outer wall with three gates. There is also an inner wall having four gates and a long entryway to the mausoleum itself. The terra-cotta army (Figure 6.3), discovered in 1974, lies in several major pits more than a kilometer from the palace. Over 180 other pits have been found, containing many other relics. To date, more than 8,000 warriors – infantry, archers, cavalry, officers, generals – plus bronze and clay horses and bronze chariots are known. In other pits, there are dancers, musicians, acrobats, gardens with clay birds, and an imperial chariot with four bronze horses in full harness. All figures are life-size, or larger, and were originally painted in lavish color. Everything was produced in a mere 11 years, at a rate of more than 700 figures per annum. This was high art produced on a mass scale. Its very conception tells us where China's scientific and technological capabilities stood at the time.

Let us focus on the warriors. They were built in pieces, each piece with its own mold: the torso was propped up so craftsmen could carve details of the armor and decoration; the hands and legs were done separately and the head was its own object, carefully finished with special tools to shape the eyes, hair, lips, and ears. When assembled, each warrior was fired in a kiln specially built for the purpose.

Next, each warrior was painted brilliantly in up to seven colors. Sources for these colors included cinnabar (mercury sulfide) for red, used on the lips and, more lightly, the cheeks; charcoal for black, for eyes, head and facial hair, as well

Figure 6.3 The terra-cotta warriors in the tomb of Chinese Emperor Qin, 3rd century B.C. See text for discussion.

as shoulder and chest armor decoration; azurite (a copper oxide) for blue, added to sleeves and collar; ochre or other iron oxide for dark red or orange, also applied to armor; burnt and powdered bone for white, for sections of clothing; malachite (another copper mineral) for green, applied to clothing decoration and footwear.

One other color was added, mainly for generals: purple. Why is this significant? Because it is manmade. Known as "Han purple," due to its abundant use during that dynasty, it is one of only two artificial colors created in the pre-Christian era (the other being Egyptian blue). Chemical analyses have shown the composition to be $BaCuSi_2O_6$, a barium-copper silicate, yet the process to make it remains unclear. Given the amount of Han purple needed for the officer corps, Chinese artisans were capable producing it at industrial-scale.

A striking fact: despite their great number, the warrior figures seem to be individuals (Figure 6.3). They have different facial expressions, facial hair, and top knots (hair styles), as well as different ages and emotional states: most appear stern, but others are smiling or wide-eyed and alert. Body shapes vary from young and thin to middle aged and stocky, and even old, pot-bellied veterans. Yet close study proves such individualism a mirage. There are eight types of faces and a similar number of body forms. Another clue is height: soldiers average 1.77 m (5'8") tall, officers 1.9 m (6'3"), and generals 1.96 m (6'5"), numbers too big for Chinese men at the time and too neatly matched to rank. We are, therefore, dealing with idealized representatives of a military force meant to protect and serve the emperor in the next life. The level of realism and detail, however, reveal that Chinese culture had developed a full appreciation for the powers of observation *and* the ability to replicate it.

The tomb, meanwhile, was built so that the ceiling bore a portrait of the heavens, while an actual landscape was created in relief on the tomb's surface. We learn of this from the *Shiji*:

> Palaces and scenic towers for a hundred officials were constructed, and the tomb was filled with rare artifacts and wonderful treasure. Craftsmen were ordered to make crossbows and arrows primed to shoot at anyone who enters the tomb. The hundred rivers, the Yangtze River and Yellow River together with the great sea, were all imitated by means of flowing mercury, and there were machines which made it flow and circulate. Above were representations of the heavenly constellations, below, the features of the land.

Archeologists believe this to be at least partly accurate. Mercury has been detected in the soil above the tomb, which remains unopened. It is assumed that fabulous relics will one day be found inside. Whether the anti-looting system remains intact will have to be seen.

Achievements of the Han Dynasty

After the Qin emperor's death, the dynasty soon collapsed and the Han took over, moving the capital to Chang'an (Shaanxi Province), eastern terminus of the Silk Road. Under the new dynasty, the city flourished as a center of political, economic, and cultural influence. By the first century C.E., the Han were trading regularly with Southeast Asia, India, Central Asia, Persia, and Rome, whose demand for silk soared under the empire.

The Han well understood the advances of the Qin state and kept, with some adaptations, the system of centralized bureaucratic control, government ownership of key industries, and imperial standards for money, measures, and writing. Related technology progressed in all areas. Legalism ended as the reigning ideology. Han rulers favored Confucian ideas, allowing Taoism and Buddhism to blossom as well. Hundreds, perhaps thousands, of local schools and academies devoted to Confucian thought were opened across the empire. Though Confucian philosophy emphasizes reverence toward elders and ancestors, the Han used a type of scientific image for the state, seeing it as a microcosm of nature similar to the human body. The good ruler understood and treated his officials as essential limbs. The emperor was no longer all-powerful but served as a medium of contact and balance between the cosmos and the citizenry.

Han rulers encouraged growth in industries and knowledge that supported a more sophisticated, even cosmopolitan style of life. Much new work went into mineral extraction, salt making, bronze and iron production, and craftsmanship in various luxuries like quality textiles, lacquer-ware, and painting. The first official census was performed in 2 C.E., while surveying and mapping programs were performed. Han maps of the first century B.C. show not just the location of rivers as in Qin times, but mountains and topography in general, plus roads, settlements, and military installations. Under the Han, the geography of China becomes a subject of study.

Some idea of the industrial scale of technology can be seen in the estimate that between about 114 B.C. and 5 C.E. no less than 28 *billion* coins were officially cast. This involved sizeable amounts of copper, tin, and also lead (added to give the alloy polish). Thus, the importance and sophistication of China's mining industry, as well as metal refining, smelting, and casting, were considerable. The Han accepted the Qin standard of a circular coin with a square hole in the middle, thereby saving metal. Coins, moreover, were never minted, i.e. struck when semisoft or in sheet form by a hammer bearing the image to be borne. They were produced by casting, from molds, thus demanding mass production of liquid metal.

The Han Era was a period of diverse innovation. Major progress in iron metallurgy came from new types of furnaces, the use of water wheels to power bellows, and also an understanding of how to control the amount of oxygen (air) and exposure to carbon-bearing gases. Iron came to replace wood and bronze in agricultural and building tools. Along with invention of an advanced plow with multi-tube seed drills came expanded food production. For irrigation, a mechanical chain pump worked either by two men stepping on treadles or else by wheels operated with animal labor was able to lift water from ditches into fields. The water wheel was also applied to trip hammers able to pound grain, freeing up workers for other tasks. Production of silk textiles was speeded up by an actual belt drive for winding fibers on shuttles and also a crank handle useful for reeling.

Another area where invention reached new levels was salt production. Salt was produced both from evaporation of seawater in coastal areas and from brines in inland areas (Sichuan Province), as shown in our opening scene with Marco Polo. By carefully observing some of these surface brine pools, one of the great engineers of the late Warring States Period, Li Bing, had concluded that they were being fed by salt springs sourced at deeper levels. Beginning about 250 B.C., he had wells dug to reach these sources, improving brine recovery. A decorative brick recovered from the Zigong site in Sichuan shows a process involving extensive and complex drilling equipment. This included a heavy iron rod with a point or wedge on one end, raised and then dropped through a bamboo tube to crack the rock on impact, with scoops used to remove rock chips. Reaching depths of 200–300 m could require more than a year. Once encountered, brine was brought to the surface and poured into a bamboo pipeline that delivered the fluid to a series of broad, shallow evaporation pans heated with wood or charcoal. In the first century C.E. it was discovered that some wells, which had caused explosions and leaked an invisible "evil spirit," had a benefit for heating. Experimenting with the spirit substance, workers found they could pipe it, light it, and use it for heating and cooking. They also found the right mixture with air so that it would still light but not explode. By about 200 C.E., they were piping the natural gas into boiling sheds, where salt was produced in larger quantities than ever before.

The Han created the position of the "grand historian" and "royal astronomer/astrologer" in one person. The tasks of this high office focused on time: responsibility for recording astronomical observations, creating the yearly calendar, predicting the course of government, and documenting important decisions, ceremonies, military campaigns, and other events. The greatest of the Han historian-astronomers, Sima Qian (ca. 145–87 B.C.), performed all these functions while writing in private the *Shiji*, an immensely important work of history covering the preceding 2,000 years. This became the model followed by authors down to the Ming Dynasty (17th century), when the *Twenty-Four Histories* of China was assembled. Sima Qian was also among the scholars to reform the old lunar calendar, dating from the Zhou Dynasty, into a combined luni-solar version with a highly accurate average of 365.25 days per year and 29.53 days per month.

The Tao of capitalism

Laissez-faire, or free market capitalism, ranks among the most powerful ideas in economics. Its basic meaning is simple: governments should not try to control or shape economic activity. "Leave things alone" is a fair translation. It presumes a natural law exists such that if individuals are free to pursue their own self-interest, the market will maximize benefits to society and be able to correct itself in any crisis. Adam Smith, who wrote *Wealth of Nations* (1776), is commonly associated with the policy of *laissez-faire*.

But Smith's great book never uses the phrase. The term came from a group of French thinkers, the Physiocrats, whose ideas had a major impact on Smith. The leader of the group was François Quesnay, a physician and medical advisor to King Louis XV, who was intrigued by the writings of Jesuit missionaries recently returned from China.

Most interesting to Quesnay were descriptions of the Chinese political-economic system. In 1767, he published his own influential book, *Le Despotisme de la Chine* (*Despotism in China*), in which he describes China as an embodiment of his own ideas, a state centered on agriculture as the source of true wealth and virtue. The ruler, meanwhile, was subject to law, not above it, and had harmony, not power, as a goal. Education was available to common people, and the best and brightest must work for the civil service.

China, as described by the Jesuits, fit all these criteria. Here was a state of great prosperity and achievement whose economy had always been agrarian, whose government used a meritocratic system, whose emperor was bound by law and custom. Quesnay wrote: "all the inventions that industriousness can discover, all the improvements that necessity brings . . . all the resources that self-interest inspires, are here employed and used profitably."

Quesnay was strongly affected by several points that writers on China mentioned. One of these was the huge volume of trade that took place *within* the country, without restriction. Another was the perception, as he wrote, that "self-interest . . . is the dominating passion of the Chinese people [and] holds them to continual activity." Last was how China proved that if a nation is in accord with natural law, "nature by herself is able to work things out" so that prosperity results. Putting these points together, Quesnay wrote (in words later adapted by Adam Smith):

> . . . farmers have no other laws but those from the knowledge they have acquired through training and experience. Imposed laws that would arbitrarily regulate their cultivation of the soil might disrupt the optimal efforts of the cultivator and interfere with the success of agriculture. The cultivator, subject to the natural order, should not be compelled to observe [any] laws other than those prescribed by physical conditions.

Smith rejected the Physiocrat's belief in agriculture as the origin of wealth and stability. But he strongly agreed with the passage above. He accepted, as well, the importance of self-interest. His experiences visiting the shops and small factories helped him see that industry, not agriculture, would be the future of modern economies and that this future would be one of ever-more increased trade. Nations would always try to separate themselves from one another, but to maximize their benefit from exchange, they needed to act as if they were part of one great whole. Without ever knowing it, China had a role in the founding of modern capitalism.

Two world-changing inventions

Han Dynasty inventors are responsible for two of the most important creations of the pre-modern era: the compass and paper. With the compass, we know neither the inventor nor the date, though related artifacts have come from grave sites of the first century C.E. We do know the purpose, however, and it was *not* navigation.

It was geomancy, the practice of divination using special signs. The device used the observation that an elongated piece of lodestone (magnetite, Fe_3O_4), if free to spin, will always return to the same position, pointing north and south.

This device is shown in Figure 6.4. It had a square bronze base (non-magnetic), 5–7 cm on a side, with a polished circle in the center. A spoon of lodestone about 2–3 cm long, representing the Plough (Big Dipper), would be placed on the polished circle and allowed to spin until its handle came to rest pointing at magnetic south. Inscribed characters show that the square base and circle together formed a diagram of the cosmos. The circle, called the "heaven plate," sometimes had characters showing the 24 directions. The square base represented the Earth, with characters indicating the eight trigrams of the *I Ching*, plus the "12 earthly branches," and 28 lunar mansions. On some examples the heaven plate was itself allowed to rotate, simulating the revolution of the Plough during the year.

Exactly how this diviner's board was used remains unknown. No text provides us with a user's manual. Compasses for navigation, meanwhile, would appear only after the 9th century C.E., becoming widely employed by 1120 C.E.

Figure 6.4 This first "compass," dating from the Han Dynasty (2nd c. B.C.–2nd c. C.E.), was actually used for divination. It has a bronze plate and spoon made of magnetite (lodestone). The spoon, about 2–3 cm (~1 inch) long, set in any orientation on the plate, spins so that the handle comes to rest pointing south. © Hans-Joachim Schneider/Alamy.

As for paper, this was invented not once but twice in Han times. The first time seems to have been during the reign of the Emperor Wu (141–87 B.C.), when hemp was used as starting material. The product was coarse and variable in quality, employed for wrapping and padding containers, not writing. Re-invention of paper is attributed by ancient sources to the official Cai Lun (50–121 C.E.), an Inspector of Public Works. In 105, he submitted a report to the emperor on a new process for papermaking and received high praise. The favor he gained did not last long: entangled in a conflict between the empress and the emperor's grandmother, Cai was accused of treason and drank poison. An official biography written a century after his death grants him back his fame and describes his innovation. It was, in fact, a kind of recycling that took as its raw material a combination of used pieces of hemp, rags, old fishing nets, and tree bark, boiled in a large vat of water. Once broken down to a suspended mass, a large, fine-mesh screen was dipped into the water and pulled vertically upward, so that a layer of randomly oriented and overlapping fibers formed in a thin sheet. This was washed and pressed and the sheet trimmed and hung on a heated wall to dry.

Manufactured this way, paper was light, thin, flexible, and cheap, a surface to replace bamboo strips for documents. This standardizing of writing surfaces was matched by an evolution in Chinese characters themselves. The so-called "model script" appeared in late Han times and thereafter remained the basic form of writing until the mid-20th century, when Mao Zedong introduced "simplified Chinese," severing past and future.

Paper would change the world. The Han Dynasty also created the closest thing to print before its invention – the famous Xiping Stone Tablets (or "Stone Classics"), in which were carved all of the Five Classics and major Confucian texts (230,000 characters). This was an effort to immortalize these works, to prevent any further changes, and to protect them from any future book burning incidents. Once complete, the tablets were placed at the entrance to China's first university, the Imperial Academy in Luoyang, founded in 29 C.E. to teach Confucianism to as many as 30,000 students. Scholars throughout the empire flocked to the site to make rubbings of the texts. Immortality proved elusive, however. The tablets, along with the university, were seriously damaged in the chaos and battles that brought down the Han Dynasty itself.

The place of science in Han society: a second look

Han emperors were open and nurturing of a scientific culture in China. Yet Han ideas about scholarship had a different orthodoxy. Many of these ideas were set down by the thinker Dong Zhongshu (174–104 B.C.), who proposed an all-embracing type of Confucianism. This stated the emperor was the basis for the state as long as he obeyed the rule of heaven, sought harmony, a balancing of *yin* and *yang*, and educated his people. Education meant learning the skills of literacy in order to study Confucian texts.

Such gave the written word particular importance. It was at this time that the *Wujing*, or Five Classics, were officially designated. At the same time, histories, biographies, commentaries, teachings, reflections, and more were produced about the state and its rulers and history. The Han Era was when the system of appointing professional scholars as government officials was fully implemented, with its rigorous examination system based on the *Wujing*. Since Han times, the words "civilization" and "culture," *wenming* and *wenhua*, have shown the authority invested in writing. Both include the character for "literature" or "writing/script" (*wen*).

In this context, science and technology took the role of servants to society. They had no place in the curriculum of the Imperial University, as advised by Dong Zhongshu. Nor were they integral to the definition of the Han "scholar." Among the most telling passages about the status of knowledge appears in the writings of Hsun Tzu (312–230 B.C.), a much admired interpreter of Confucian philosophy in Han times:

> You glorify Nature and meditate on her,
> Why not domesticate her and regulate her?
> You obey Nature and sing her praises,
> Why not control her and use her? . . .
> You meditate on what makes a thing,
> Why not so order things, that you do not waste them?
> You vainly seek into the cause of things,
> Why not appropriate and enjoy what they produce?

Astronomy

In China, the heavens were closely observed from a very early time. This was true for the other civilizations we discuss, certainly, but China is unique in several interesting and intriguing respects. These include the following.

1. Chinese astronomy was based on the North Star and the circumpolar constellations. It did not use the horizon for reference and so did not focus on the heliacal rising of stars.
2. For locating points in space, the Chinese invented an equatorial system (like our modern one) based on the Earth's equatorial plane extended into space as a celestial equator (other scientific cultures we have discussed used an ecliptic system, based on the plane containing the Earth's orbit around the Sun). While Chinese astronomy did use the ecliptic after contact with India and Greece, by the Song Dynasty the equatorial system was again preferred.
3. Chinese constellations show some degree of overlap only with those of India. Early astronomers divided the sky into 28 lunar mansions, just as was done in the *Vedas*. The names and included stars of each constellation are mostly unique and were not changed with contact between China and other cultures to the west.
4. Observations by astronomers and astrologers gave equal weight to all celestial phenomenon, including comets, meteors, supernovae, and also sunspots

(earliest recordings of these were in China) and maintained a continuous record of such events for over a thousand years, data that has proved of huge importance to modern scholars. In other cultures, such phenomena were regarded as anomalies and not greatly studied.

5 Astronomical observations were demanded not only for calendar-making and omen reading but because of belief in the direct correspondence between celestial events and the ruler and his officials. Under a just regime, the heavens followed their normal course; when an unjust government was in power, unexpected events (comets, supernovae, etc.) would occur, signaling a need for change, penance, or the possibility of future disasters.

6 Thus, the practice of astronomy was deeply linked to government needs and demands. It was not merely an advisor but an integral part of the civil administration. This appears to have been the case from at least the Zhou Dynasty onward.

7 From Han times, astronomy and astrology were given separate imperial bureaus. Royal astrologers focused on observation of planetary motions and the reading of signs provided by astronomers. Astronomers were responsible for the calendar each year, predicting celestial events (eclipses, comets, etc.), determining the seasons, and weather.

8 Astronomical work as strongly supported by the state was kept somewhat secret. This included instruments as well, which seem to have been closely held for many centuries. Conditions relaxed during Song times, when astronomy and mathematics were subjects for study in schools and were included in the civil service examination.

The emperor himself appointed his official astronomers and astrologers. To do their work, these men meticulously charted as many stars and events as they could. By the end of the Han Dynasty, they had mapped 1,464 stars (442 more than in the *Almagest*) and grouped them into 283 constellations. They had directly observed the Sun through "lenses" of jade, recording the first sunspots in 28 B.C. They had built complex instruments to measure major movements. They had defined the celestial realm as a sphere but the Earth as a square, an idea that continued for nearly 1,500 years. They also applied *wu xing* to the skies, the five planets considered as essences of the theory.

The basic structure of the Chinese heavens began with the North Star at the center, representing the ruler/emperor, with the circumpolar constellations as his palace, family, and officials. This central region was the "Forbidden Purple Palace," whose shape was used as a model for the capital city at two times. The walls of Chang-An, capital of the Han Dynasty, were built in the shape of the most northern and southern circumpolar constellations, the Big Dipper and Sagittarius, with the city itself oriented northward. A second version is preserved in the famous Forbidden City, built in Ming times, located in the north district of Beijing, with the emperor's quarters in the northern part, aligned with the pole star.

The rest of the celestial sphere was divided into four quarters associated with the four cardinal directions. Each quarter had an animal and a color from the *I*

Ching and one of the Five Agents. The four quarters are: 1) Black Tortoise, representing north, winter, and also the *wu xing* water; 2) Blue Dragon, which is east, spring, and wood; 3) the Red Bird, for south, summer, and fire; and 4) White Tiger, for west, autumn, and metal. Each animal figure contained seven constellations, which could include only two or three stars or as many as 15. The total 28 constellations defined the "lunar mansions" of astrology. They were used to divide the celestial sphere into 28 sections (like slices of an orange) used to mark the monthly progress of the Moon. For locating individual stars, the Chinese devised a system of 365.25 degrees (units) for the circumference of a circle, based on the number of days in a year, and applied this to create a latitude and longitude grid for the celestial sphere.

Some influence between Chinese and Indian astronomy/astrology is suggested by two similarities. First, Hindu astronomy also defined 28 lunar mansions or *nakshastras*. These are given in the *Atharva Veda* and also in the later *Vedanga Jyotisa*. Chinese astronomy/astrology also included nine planets, based on the seven visible bodies and on two "invisible" planets associated with the ascending and descending nodes where the paths of the Sun and the Moon intersect. These two bodies, *Chiao Chu* and *Chiao Chung*, correspond with the Hindu *Ketu* and *Rahu*, discussed in our chapter on India.

The importance of astrology in political events can be illustrated by the following example. Several texts from the late Warring States Period and Han Dynasty (including the *Mencius*, *Shiji*, and *Bamboo Annals*) tell of a rare massing of the five planets in 1059 B.C. This took place in the Red Bird and led King Wen of the Zhou to begin actions intended to challenge the Shang regime. Though he died before the overthrow could be achieved, his son King Wu took up the cause. Yet when this ruler was informed of Jupiter's retrograde motion out of the Red Bird, he halted his attack on the Shang armies. Waiting two years (1048 to 1046 B.C.) until Jupiter reappeared in the same quarter and followed its "normal" path, he launched his assault, ending the Shang Dynasty. King Wu, therefore, claimed he had acted on the urging of Heaven and had been truly designated the new "son of heaven."

The primary importance of observational astronomy is apparent from many examples. Comets, due to their meaning as omens, were carefully observed, divided by apparent type, and recorded. Atlases of comets were produced as early as the Warring States Period. The first recording of sunspots in 28 B.C., was followed by at least 165 more such recordings up to 1638. In 11 B.C., the polymath Liu Xiang collected lunar observations in graphical form, recording the eastward advance (around the Moon's orbital path) of the lunar apsides (points of maximum and minimum distance from the Earth). In 725, the famous Buddhist monk and, later, court astronomer Yi Xing (also: I Hsing; 683–727), built an armillary sphere with sighting tubes and took readings of many star positions, finding some had shifted since the Han Era beyond what could be explained by the Earth's precession. This led him to propose the stars may not be fixed, a radical idea not widely accepted. There were also recorded observations of supernovae, like those of 185 C.E. (Vela Supernova) and 1054 (today the Crab Nebula). Chinese astronomers identified as many as 20 candidate supernovae, which they called "guest stars." Modern astronomers use Chinese records as a basis to search for supernova remnants in space.

China was the site of perhaps the largest astronomical field project ever performed. The Tang Astronomical Bureau in 724 carried out a geodetic survey to gather data for solar eclipse predictions, calendar adjustments, and for measuring the length of a degree of meridian (longitude). Nan-Kung Yue, the bureau head, stationed officials at ten sites along a north-south transect between 17°N (Vietnam) and 51°N (Russia, south of Lake Baikal), a distance of 2,500 km. Measurements at each site included the angular altitude of the North Star and, taken simultaneously with identical gnomons, the shadow lengths of the Sun at noon on the winter and summer solstices. The data were then given to Yi Xing, whose final result, known to be an average (a degree of longitude has different lengths, depending on how close one is to the equator) was 123.7 km, compared to the modern figure of 111 km.

Overall, we are fully justified in finding Chinese astronomy extremely impressive for a number of reasons. In observation, China remained unsurpassed until Tycho Brahe and the telescopic era. Chinese astronomers, however, did not develop analytical models of the planets. They were never much concerned with theories about the details of planetary motion, as were the Greeks, Babylonians, and Indians.

Mathematics

The evolution of mathematics in China is known from many preserved texts. Most are compilations of existing knowledge, intended for teaching, studying, or reference.[1] Like the *Rhind Papyrus* in ancient Egypt, they collect a variety of problems and solutions from various eras. Other books provide commentaries, above all on the *Jiuzhang Suanshu* ("Nine Chapters on the Mathematical Art") a core text for many centuries. One interesting point we might contemplate: a number of these books, like the famous *Zhou Bi Suan Jing* ("Arithmetical Classic of the Gnomon and Circular Paths of Heaven"), are dialogues between master and learner – a form we have seen nearly everywhere in ancient science.

Calculation was being done at sophisticated levels even by the Shang Dynasty. Oracle bones record a complete number system with decimal place-value. Separate symbols existed for powers of ten, so that to write the 2,450, one would use: two thousands, four hundreds, and five tens (six symbols). No zero, therefore, was needed. Though individual symbols evolved over time, this basic system has continued down to the present, in this form: 一 二 三 四 五 六 七 八 九 十 (1–10); 千 (1000); 万 (10,000). For most of its history, however, this system was used to record figures, not to calculate or to work with equations. For this, a wholly new scheme was invented.

Pressures of an empire, expanded trade, and tax collecting urged the creation of a means for rapid computation. Here, the Chinese used counting rods that could be arranged quickly to form numbers of any size and to perform operations

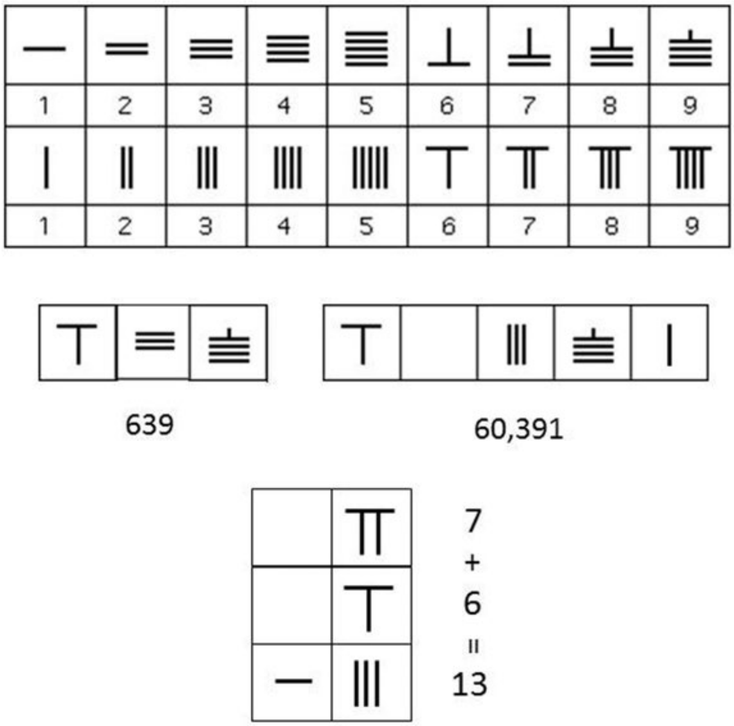

Figure 6.5 Chinese rod number system and sample calculation. This system, as shown in its mature phase, dates from the Han Dynasty (2nd c. B.C.–2nd c. C.E.).

(Figure 6.5). By Han times, these rods were arranged in vertical and horizontal combinations read in decimal notation. Thus the symbol for 6 in the fourth place from the right was read as "6,000" or in the second place as "60." To prevent confusion if rods were closely placed, both combinations were used for 1 through 10 and applied alternately between place notations. This is shown in Figure 6.5 for the numbers 639 and 60,391. Eventually, different colored rods were introduced to signify positive and negative numbers; methods were developed to represent algebraic equations with two or more unknowns. Rods began as small bamboo sticks bundled with string, but became shorter, even rectangular over time, made of iron, wood, even jade. Though elegant and useful, counting rods had their limits. Complex operations needed lots of space; clumsiness could destroy an entire operation. The system also seems to have prevented the spread of equally useful forms of calculation, such as the abacus, which became common only after the Tang Dynasty.

The oldest mathematical works of major importance are the *Zhou Bi Suan Jing*, dated tentatively in the late Warring States Period (ca. 500 B.C.), and the *Suanshu Shu* ("Book on Numbers and Computation"). Both are compilations of problems for study. The *Zhou Bi Suan Jing* seems to have been revised and enlarged into the

Han Dynasty at least. The *Suanshu Shu*, by contrast, is more of a single, completed text and, therefore, more reflective of mathematics during its period. Discovered in 1984 in the tomb of an early Han Dynasty government official, it was composed between 202 and 186 B.C. It is written in ink on 180 strips of bamboo and includes 69 problems presented in standard form of question-answer-method. These cover basic arithmetic, fractions, progressions, interest rate determinations, unit conversions, error corrections in tax amounts, area and volume calculations, and approximate square roots. Not a systematic treatise, the text is a collection, probably assembled from other works (the bamboo strips were found unbundled). It is repetitive and even duplicative in parts. The medium itself may have urged each problem to be written separately, on a separate set of strips, later combined with others. Despite all this, it is a window into the use of mathematics in the early Han Era and offers some crucial indications of Chinese society in that time.

The first part of the text mainly deals with fractions. One of its first rules is written this way: "The method for multiplying a part [is] always: the denominators multiply together . . . the numerators multiply together." A more interesting problem involves "simplifying parts," i.e. reducing fractions. The method is this: "What can be halved, halve it . . . [Then] take the numerator from the denominator. [If it is] the lesser, take the denominator from the numerator. When [the numbers on the sides of] the numerator and denominator are equal, take that as the divisor." The problem given in the text is to simplify 162/2016. Halving this, we get 81/1008. From here, the method tells us to do this:

$1008 - 81 = 927$
$927 - 81 = 846$
$846 - 81 = 765$
. . . etc. until we get to
$117 - 81 = 36$
$81 - 36 = 45$
$45 - 36 = 9$
$36 - 9 = 27$
$27 - 9 = 18$
$18 - 9 = 9$.

The number 9 is therefore the final divisor, so that 81/1008 (divided by 9) simplifies to 9/112.

Next come rules for practical problems. One example involves estimating how much hulled grain can be expected from an unhulled quantity. We read: "seeking hulled [millet] from unhulled, 3-fold it and take 1 for 5; seeking wheat from unhulled, 9-fold it and take 1 for 10." That is, for millet, triple the total and divide by 5; for wheat, multiply the total by 9 and divide by 10. These kinds of algorithms comprise pretty much all of the solutions. They tell us how to calculate the amount of earth that must be removed to make a ramp into a tomb; the volume of grain that exists in a natural, cone-shaped pile of a given height and basal circumference; the volume of a round pavilion shaped as a frustum (a cone sliced somewhere below its vertex). While the algorithms provide approximate answers in such cases, the implied value of π being 3, their consistency argues for real standardization.

Indeed, reading through this text, a society begins to emerge from the whirl of figures and rules. It is a society where calculation is applied to a great many aspects of daily life, where numbers have real, concrete power and are employed not only for utilitarian purposes but to impose forms of normalcy and control on human beings. Consider, for instance, this "story problem" about a man who makes and delivers charcoal for the government. In a day, working in the mountains, "he makes 7 dou of charcoal and [carries] it to the cart. The next day, he [brings his cart] to the office [and delivers] . . . 1 shi. Now, it is desired that carrying charcoal . . . he should take [it] all the way to the office. Question: how much charcoal [will now] arrive each day?" Because 1 shi = 10 dou, the worker must have some charcoal stored away; he has some days made more than 7 dou. Life is not easy. But now it will be harder. He must no longer alternate days of production and delivery; he must deliver each day the charcoal he makes, however long it takes to make it. He will now have a strict quota, based on his present work rate, which actually includes some rest time now to be eliminated. For the solution, using his current rate of production, the man must be able in ten days to make ten times 7 dou (70 dou), which equals 7 shi (1 shi = 10 dou) and which he would normally transport on 7 alternate days (1 shi for each delivery day); so it would take a total of 17 days to make and deliver 70 dou, resulting in 70/17 = 4 + 2/17 dou per day.

By all accounts, the *Suanshu Shu* seems to have been a practical reference or review text for government officials. The implication of this last problem is that part of their task was to look for, and find, places in Han society where productivity on behalf of the state could be increased. Mathematics provided a rational, if unforgiving, means to do this. For the charcoal maker, the new system he must adopt takes no account of the process of production itself, e.g. that it requires days in special kilns that must be closely monitored and cannot simply be turned off at a certain time so deliveries can be made.

When we turn to the *Jiuzhang* ("Nine Chapters"), written two to three centuries later, we find a more orderly and advanced text, in nine parts with 246 problems. These problems represent a compilation from different periods of time, perhaps going as far back as the early Zhou or even Shang dynasties, though it is difficult to confirm this. There is certainly overlap with the *Suanshu Shu*, yet the material is much more highly organized and in a more concise, clear style; each chapter begins with simpler problems and moves to the more complex, at times showing multiple solutions and also using visual diagrams, which the *Suanshu Shu* did not do. Overall, in both mathematical and literary terms, it is a major advance for its time. So useful was the *Jiuzhang*, in fact, whose author is unknown, that it remained the key text of mathematics in China and in surrounding East Asia for more than 1,400 years. Two of its most famous commentators, Liu Hui (3rd c.) and Yang Hui (13th c.) are themselves separated by an entire millennium.

When we look at the topics covered, it is easier to see why the *Jiuhang* was fundamental for so long. In order, they include: 1) rectangular field areas (38 problems);

2) exchange of food grains and their value proportions (46 problems); 3) progressions related to money, distribution of goods, workers (20 problems); 4) dimensional calculations of fields and square/cube roots related to areas and volumes (24 problems); 5) engineering projects such as canals, dikes, city walls, worker hours, and volume calculations (28 problems); 6) equitable taxation, distribution of quantities, soldiers, grain, rent, with multiple variables (28 problems); 7) excess and deficit problems for commodities, money, animals, land, involving linear and simultaneous equations (20 problems); 8) more complex linear and simultaneous equations, concerning mainly grain, animals, but using matrices and rules for negative numbers (18 problems); and 9) problems solved using right triangles and Pythagorean theorem, known as *Gou Gu* (24 problems).

What types of problems, specifically, were included? Early chapters have similar material to the *Suanshu Shu*. Chapter 1 has basic questions: "There is a field, width 3 1/3 bu and length 5 2/5 bu; find [the area] of the field. Answer: 18 bu" (no indication of square units). Chapters 2 and 3, meanwhile, are focused on problems of proportion solved by the "Rule of Three,"[2] a much-favored method among Chinese merchants, officials, and military officers. Chapter 4 handles more complex matters, including square and cube roots, showing the Chinese could routinely extract square/cube roots from non-integers many centuries before the West did.

Chapter 5 draws special interest, for it returns us to stories of conscript labor and bureaucratic treatment of workforce needs, thus to the actual workings of Han society. One problem, for example, asks us to find the volume of a trapezoidal dike. This might at first seem rather mundane, a matter of everyday planning and nothing more. But in fact it tells us the Chinese were very precise about these kinds of projects, treating an ordinary small-scale section dike – of which there must have been hundreds of thousands, perhaps even millions – as an architectural project. This seems impressive. But the problem has a second part: "The work capacity of a person in winter is [number given]; [based on the total dike volume] find the number of workmen needed. Answer: 16 2/111 men." So it would seem the official performing this calculation has a decision to make: whether to use 16 men, who will work a little harder, or 17 men, who may be allowed a small rest now and then. We see workers being considered in what might seem a very "modern" 19th century capitalistic way – as productive and disposable units.

Modern readers are often drawn to the book's final chapter due to its focus on right triangles and the Pythagorean theorem. As we have seen, this theorem was discovered or proven by all the major ancient civilizations, in some cases independently. Given its crucial importance for land surveys, architecture, astronomy, and more, it is not surprising that this should be true. The Chinese knew it as the *gou-gu* theorem, *gou* ("leg") meaning the base, *gu* ("thigh") the height, with *xian* ("bowstring") as the hypotenuse. The *Jiuzhang* shows that, like the Rule of Three, it was established knowledge by Han times. It is simply described as the "method of *gou gu*, [which] says: self multiply each of *gou* and *gu*, add and extract the square root to obtain *xian*." Thus, it gives the $a^2 + b^2 = c^2$ relation but without proof. The first actual proof known is given by the *Zhou Bi Suan Jing*, which, as noted, is also a compilation of problems and solutions from different times, starting, it seems,

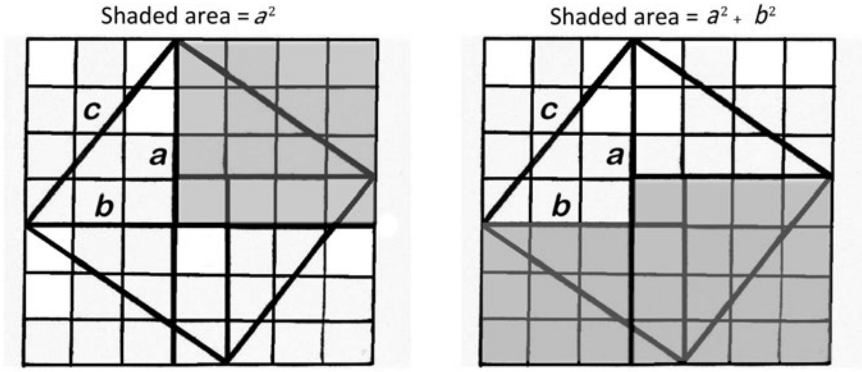

Figure 6.6 A pictorial proof of the Pythagorean theorem, known as the *gou-gu* theorem. First, shaded squares are made from the sides *a* and *b* (left figure; only *a* square is shown). Next, the *a* square is dropped down next to the *b* square to form a single area (right figure). We can now see that the two triangles in this area that lie outside the reference square (tilted, with side *c*) will completely fill the rest of the interior of this square, which equals c^2.

in the Zhou Dynasty (some scholars insist on dates as early as 1000 B.C., others that the Warring States Period is more likely). As shown in Figure 6.6, the proof is visual in nature, though nonetheless quite elegant and convincing.

Elegant, too, are some of the problems in the *Jiuzhang* that may date from a much earlier time, e.g.: "In the middle of a pond that is 10 chi across there grows a reed whose top reaches 1 chi above the water; when pulled to the edge of the pond, the reed just touches at the water line; what is the depth of the pond and the length of the reed?" The solution is shown in Figure 6.7, both using modern algebra and the method in the *Jiuzhang*.

What do we learn from this brief overview? The *Nine Chapters* seems to treat nearly every major domain necessary to governing a major state: agriculture and food, trade and commerce, money and taxation, labor, architecture, and though not shown above, legal issues and the military were also included. Mathematically, meanwhile, we see that each rule (algorithm) given for solving a problem works as a verbal formula. Someone else has done the mind work; all that is needed is to apply the formula. Thus, there is a difficulty in saying that this book reveals what was actually *known* by trained officials, merchants, etc. It is more likely that a tiny minority of individuals actually understood the mathematical concepts involved.

A vast amount has been written about the *Jiuzhang*, especially since the publication of Joseph Needham's pathbreaking *Science and Civilization in China* series. Needham suggests it served both as a textbook and practical handbook. That it set a standard for many centuries, beyond the Song Dynasty, is reason to reflect on such influence by a single text. Advanced and sophisticated as it truly was for its time, it may have proven an impediment to progress in later ages – similar to Aristotle and Ptolemy's work in the West. Such may help explain why Euclidian geometry, when introduced to China in the early 17th century, had so little impact.

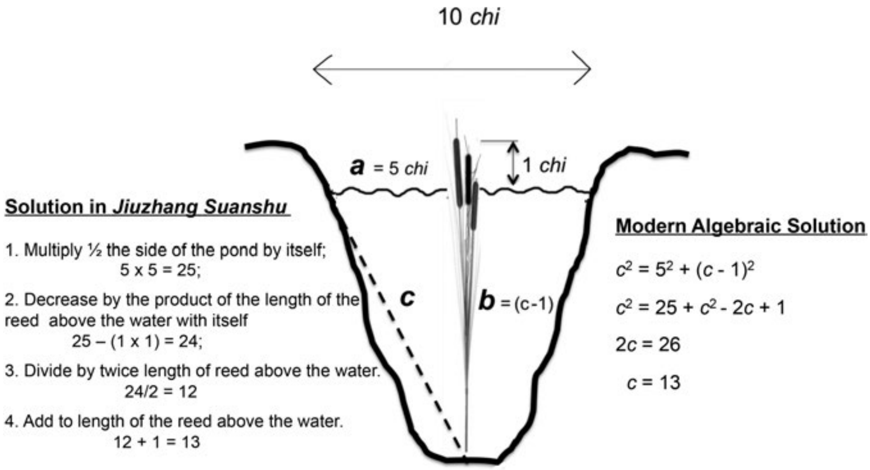

Figure 6.7 A problem from Chapter 9 of the *Jiuzhang Suanshu* ("Nine Chapters on the Mathematical Art"). Solutions from the original text and using modern algebra are shown. The problem states: "In the middle of a pond ten *chi* in diameter, a reed grows 1 *chi* above the water. When pulled to the edge, the reed just reaches at water level. How long is the reed?"

Medicine

Chinese medicine is as old as Chinese civilization. Though founded on concepts much different from those of modern western science, it shows overlap that might surprise the physician of today. By the Tang Dynasty (618–907 C.E.), practitioners knew that blood moves through vessels in the body in a system controlled by the heart. They knew that its passage through the body happens rapidly, though their estimate of half-an-hour was a bit over the actual time of one minute. Chinese doctors also emphasized preventing illness through diet, exercise, and rest. Despite touches of number mysticism, Chinese medicine relied mainly on empirical knowledge and on therapies tested for many centuries.

As with India, we need to accept an obvious fact: traditional Chinese medicine (TCM) served its people for huge lengths of time and so must comprise an effective system in some areas. TCM, moreover, has now spread widely outside of China, gaining use in many nations and acceptance by such institutions as the U.S. National Institutes of Health and the French Academy of Medical Sciences. Licensed practitioners, both in herbal therapy and acupuncture, number in the many thousands.

TCM is based on the combined theory of *yin-yang* and *wu xing* (five agents). It involves the classification, diagnosis, and treatment of illness and so makes up a total medical system in modern terms. Its forms of therapy use herbal medicines, acupuncture, and dietary adjustments, sometimes with other components like exercise and sleep changes. It treats illness as a disruptive condition to be improved not only by specialized drugs but by changes in lifestyle and life habits. TCM is thus often described as concerned with the "whole person."

It was during Han times that TCM became a professional practice, with a canonical text, the *Huangdi Neiching Suwen* ("Yellow Emperor's Classic of Internal Medicine"; c. 2nd–1st century B.C.). From this work, we see that TCM uses ideas of flow and communication. The human body is a network of channels, meridians, storage sites (organs), and orifices for the transport of blood and *ch'i*. The heart is the center, controlling the movement of the blood and the precise qualities of the pulse, which, therefore, is a focus of diagnosis. All parts of the body are linked by the network of flow and affect each other in dynamic and subtle ways. The body is also affected by external influences, which gain entrance through the various orifices. Interaction between body and cosmos is constant and a major factor in health. Outside influences include astronomical phenomena, climate and weather, the seasons, time of day, working conditions, other people, and family. Also central are the "five states of mind" (joy, anger, sadness, anxiety, fear), which can have both good and bad effects. Health results from dynamic balance and proper cooperation among all bodily elements and influences. It is, therefore, a condition of continuous response, adjustment, and rebalancing. Even if we do the same exact things each day – eat the same foods at the same times, perform the same exercises, sleep in the same bed for the same number of hours – changes always occur, in the weather, in our work, our age, our relationships. Our bodies, minds, and spirits must constantly adapt to the natural and human worlds. Looked at in this way, "health" is no small achievement!

The *Book of Rites*, one of the Five Classics, warns its readers to reject any medicine from a doctor whose family is without at least three generations of physicians. Even in the early Han Dynasty, there were few professional schools for medical training and most physicians learned their craft through family apprenticeship and study of the *Neiching* text.

The Neiching: the Yellow Emperor's Classic of Internal Medicine

The *Neiching* has been used continuously for more than 2,000 years. Like so many ancient texts of major importance, it has the form of a dialogue. The two speakers are the mythological Yellow Emperor, Huangdi, who tradition says reigned from about 2700–2600 B.C., and his famed physician, Qi Bo. Scholars point out that the text is really an anthology, a selective compiling and rewriting of older works, with new material added over time. Sizeable portions are poetry, which may mean they began as oral material. Transmission of the text is imperfectly known, as it wasn't printed until the Song Dynasty. Its poetic, metaphoric qualities have allowed for flexible interpretation, thus different schools of practice.

The work is divided into two main parts. The first part, *Suwen* (Basic Questions), deals with organs and meridians, as well as the principles of diagnosis and treatment. This part has sections on the two primal fluids, blood and *ch'i*, their relation to the seasons and also to dreams and forms of mental illness. A second part, the *Lingshu* (Spiritual Pivot), is a manual of acupuncture and also discusses the theory of *yin-yang* and *wu xing*. Here we learn that the body contains the "five depots" (liver, spleen, heart, lung, and kidneys) and that each organ also corresponds to one of the five agents (*wu xing*). We also learn that human anatomy, like the circumpolar constellations, provides an image of the state. The heart, as the emperor, is the creator of the blood and the residence of the spirit. The lungs help force the blood through the body and thus act as the emperor's primary minister, with the other ministers as stomach, kidneys, etc. There is continuity between the heavens, the state, and the microcosm of the body.

The *Neiching* stresses that good or bad health results from the interaction between choices we make and that are made for us by society, events, etc. These choices can either aid or upset the specific balance of *yin-yang* unique to our person. Diet is an essential factor. Dominantly *yin* foods (e.g. vegetables, beans, most fruits) cool and moisten the body and are best in warmer months. These must be complemented by *yang* nutrition (e.g. meats, nuts, ginger, spices), which are warming and drying and best in colder months. Preventing disease starts with observing one's own bodily and mental response to different foods, thereby discovering the balance that maximizes a sense of well-being. A similar approach applies to exercise and rest. *Yin* movements are "soft," like yoga or Tai chi, and emphasize stretching and relaxing, while *yang* exercise is more energetic, like lifting weights or running. A *yin* form of rest, meanwhile, would be sleep, while a *yang* form would be meditation.

What of diagnosis? Chapter 5 of the *Suwen* says that when physicians examine a patient:

> They inspect the color and press the vessels.
>
> First they distinguish yin and yang (examining the bodily sectors of each)
>
> They investigate what is clear and turbid [in the patient's complexion] and know the section [where the disease is located in the body]
>
> They observe [the patient's] panting and breathing, they listen to the tones and voices [of the body] and they know what one is suffering from . . .
>
> They press at the foot-long section [under side of the forearm] and the inch opening [just below the wrist, where the pulse is taken],
>
> They observe [whether movement in the vessels] is at the surface or in the depth, smooth or rough, and they know the location where disease has emerged. [If] in their treatment they commit no mistakes, this is because in their diagnosis they do not miss [anything].

The *Neiching* teaches that there are six different pulses, three on each wrist, each linked to a particular part of the body and highly responsive to even the smallest effects of illness. Described are more than 30 different pulse patterns, termed long, short, hot, cold, rough, slow, strong, and scattered. Actual descriptions of these are often given as metaphors. A normal heart is felt by beats "strung together, resembling a string of pearls;" a diseased liver feels as if "one's fingers passed along a bamboo cane;" a normal spleen, resembles "a chicken stepping on the earth." These tell us that the physician needed a great deal of tutoring and experience.

Overall, the *Neiching* is a highly multifaceted text that demanded years of study. Yet it has underlying themes. One is that people sometimes cause their own illness but other times do not. For illnesses due to our own choices, some are obvious (too much eating, drinking) but some are subtle and require age to understand. Therefore, the issue of responsibility is complex. Ultimately, both the person and the physician must seek prevention, the final goal. As the *Neiching* puts it: "To provide medicines for diseases that have already developed . . . is similar to the actions of those who begin to dig a well after they have become thirsty."

Acupuncture

Like other parts of TCM, acupuncture is probably much older than its first appearance in medical writings. Sharpened pieces of bone and rock as old as 6000 B.C. have been interpreted as possible forerunners of acupuncture needles. But the *Neiching* text gives us the first clear evidence of a fairly unified system, based in practice, teaching, and apprenticeship.

Simply defined, acupuncture involves the shallow insertion of thin needles at specific points along the body. These points correspond to places where the flow of *ch'i* can be intercepted and the balance between *yin* and *yang* that gives rise to *ch'i* reestablished. These acupuncture points occur along meridians. There are 12 standard meridians, divided into *yin* and *yang* groups. Each meridian is a pair, corresponding to the right and left sides of the body. Depending on the specific school of acupuncture, there are 350–400 "acupoints" on these meridians, extending to nearly every part of the body.

The *Neiching* states that when the acupuncturist treats a patient, "the first needle insertion can dispel the *yang* evil, the second needle insertion can dispel the *yin* evil, and the third needle insertion can draw the *ch'i*." When the *ch'i* is "drawn" or contacted, the physician feels the needle growing heavier, as if it were pulled to a magnet. The patient feels this as a numbness or soreness in the needle's location. It shows the treatment is working. The *Neiching* mentions different types of needles, e.g. gold, silver, copper, zinc, iron, divided into those that would create an energizing response in the body and those a more calming effect. The same points used in acupuncture are also those targeted by the practice of moxibustion, which involves the burning of small mounds of resin or other herbal cones and cylinders (moxa) to add heat at key places.

The practice of acupuncture remained a core part of TCM until the 1800s, when the influence of western medicine resigned it to a "folk remedy." Between the Tang and Ming Dynasties (7th–17th centuries), therapy continued to be refined, formalized, and adopted by Japan, Korea, and Vietnam, where it then found a new life of its own. In China, it was officially outlawed in 1929, along with most of TCM. Only in the 1940s was it brought back again by Mao Zedong, who reportedly saw its effects on sick and wounded soldiers during the Long March (1934–35) when no anesthetics or medicines were available.

Since the 1970s, the practice has spread to many parts of the world and been cautiously endorsed by official medical institutions. In the West, it is used to treat post-operative nausea, dental pain, back pain, and headache for millions of people. It has been found most effective for pain relief and raising the pain threshold and is now often integrated into therapy. Its beneficial effects, when they occur, may be delayed for an hour or two but often last for up to two weeks and sometimes far longer. Insertion of the needles is not painful; any soreness is minor and short-lived. Modern scientific studies cannot yet explain how acupuncture works.

An age of exploration that might have been

Traditional focus on the Silk Road overlooks that for 450 years, China was the greatest sea power in Asia. Maritime trade with Southeast Asia, India, Sri Lanka, and other parts of the Indian Ocean began as early as the 7th century. Yet China's real era of sea power came with Song Dynasty innovations in shipbuilding and navigation (the compass), expanding not just trade but views of the world. Maritime commerce extended to the Islamic empire by the early Ming Era, by which time China had created sophisticated maps of Asia and beyond.

It was at this point, in 1402, when the throne was usurped by a prince, Zhu Di, supported by an ambitious eunuch, Zheng He (1371–1433). Zheng was tasked with a series of massive naval expeditions. Between 1405 and 1433, seven such voyages set sail, each with dozens, even hundreds of ships, and tens of thousands of soldiers. The largest ships were wonders of naval engineering: 122 m (400 ft) in length, with nine masts, able to carry thousands of tons of cargo; they utterly dwarfed anything else in existence. The fleets followed trade routes, stopping at major ports in Sri Lanka, India, the Red Sea, Persian Gulf, and East Africa.

What goal did these missions serve? From their size and their actions – Zheng He demanded each kingdom declare itself a vassal to the Ming emperor, giving demonstrations of force, offering gifts (gold, silver, silk), and receiving tribute in return, including exotic specimens (ostriches, zebras, giraffes) – we see the aim was imperial. The voyages did not plant colonies or seek to enslave native peoples. But the sight of hundreds of ships spread out over many kilometers of ocean, approaching the shore like a vast tide, shows they were there to establish China's superiority and power and to extend its influence.

The last four missions were recorded by a Chinese Muslim, Ma Huan, who knew Arabic and acted as translator. His notes were gathered and printed as *Ying Yai Sheng Tan* ("Overall Survey of the Ocean's Shore"), a book of 20 chapters, each describing political, economic, military, and religious aspects of a locale. There is also much ethnographic information, plus botanical and zoological observation. An example for Calicut, southwestern India: "The *mu-pieh-tzu* tree is more than ten *chang* (102 ft) high; it forms a fruit which resembles a green persimmon and contains 30 or 40 seeds; it falls of its own accord when ripe; the bats, large as hawks, all hang upside-down and rest on this tree." In fact, seeds from this fruit had antiseptic properties, used to treat wounds, abscesses, and more. The *Ying Yai Sheng Tan* thus represented a new source of knowledge for China, similar to the reports sent back only a few decades later to Europe by Spanish "visitors" to America.

Travel and exploration, we know, were crucial elements in the growth of modern science. This included studies of botany, zoology, geology, and astronomy. Would further voyages by Chinese fleets have resulted in similar scientific knowledge? Ma Huan's book certainly suggests as much. But we will never know. Zheng He died in 1433. A new emperor sat on the thrown, and the officials who supported such missions lost influence to those who objected to such displays of majesty abroad when needs were great at home. The fleet was ordered destroyed, the shipyards closed, and further voyages forbidden. Many records from the missions were burnt and Zheng He himself was even eliminated from most official histories.

Metallurgy

Judged by modern standards, ancient Chinese metallurgy was remarkably advanced. This came from pottery. Understanding of clays and kilns led to molds for casting and fire for forging. By the Zhou Dynasty, Chinese kilns could reach temperatures over 1,100°C, enough to melt copper (1,083°C) but also high enough to smelt iron.

Detailed scientific study of ancient metals, using chemical analysis, electron microscopy, proton x-ray fluorescence, and other techniques has provided much valuable information on China's achievements. One result has been to confirm that the Chinese employed a different approach than other cultures, who relied on the so-called "lost wax" method. Lost wax involved making a full-sized model out of beeswax and resin, then packing it in clay, with a hole at the bottom, another at the top, and an air vent. The packed model is then fired, during which the wax melts and runs out the bottom. Inside the clay is the hollow mold left by the wax. This is then filled with molten bronze (through the top hole), which is allowed to harden and is then worked with tools for inscriptions and other decoration.

In contrast, Chinese craftsmen employed piece mold casting, which remained dominant for many centuries. Here, a full-scale model of the final object is made out of clay (not wax), then allowed to dry and harden. The model is then encased in a new layer of clay, also allowed to dry. This layer is cut into sections, which are fired, so that, when reassembled, they serve as the mold for casting. If the product is to be a vessel of some kind, with an empty space in its center, a core has to be fit into the final mold, with spacers keeping an equal distance from the walls. The mold is then put back together and the molten bronze poured in and allowed to cool. Small, hidden vents in the mold let air escape as the liquid metal filled the space. After cooling, the object was polished, no further working of the metal being needed.

Piece-mold casting may seem clumsy compared to the lost-wax method. It was more time consuming, needed more labor and clay, and was limited in the range of shapes it produced. But it had advantages. It could yield precise surface decoration with intricate designs. It allowed for writing, which, in the form of Chinese characters, has always had a deep aesthetic dimension. It forced metalworkers to invent complex forms through sequential casting. This was done to add handles, horns, ears, etc. to the primary mold. Such pieces were soldered on – a technology other civilizations did not develop until much later. "Clumsiness" led to innovation, in other words.

From the later Shang Dynasty, we see a striking evolution from small, artisan bronzes created in workshops to massive vessels produced by a factory-like system. This new, large-scale system appeared at the same time as the first cities. It is evidence of a whole new society with class stratification, specialty professions, an elite ready to spend lavishly and acquire objects embodying their status and power. In place of wine cups and ornaments, we have standing tripods weighing hundreds of kilograms (Figure 6.8). Single tombs of royal family members and high officials have yielded more than a metric ton (2,200 lbs) of bronze. Such quantity is unknown in any other civilization of the pre-Christian era. Decorations included figures of dragons and other mythic creatures, sophisticated running designs, plus writing that spoke of rites and duties.

All of this sparks the imagination. We can see mines worked seven days a week, copper, tin, and lead pouring into the cities. At open-pit and underground mine sites, workers would break up veins of ore with stone and bronze tools. In Tonglushan of Hubei Province, vertical shafts 60 meters (200 ft) deep were excavated, with horizontal tunnels supported by wood framing. At every mine, smelters were busy night and day, producing ingots for sale in the regional capitals. There were often jobs available. Workers grew ill from inhaling the particle-laden gases. In the cities existed an army of specialists working large-scale forges, with crucibles of varying sizes in which liquid metals were carefully mixed: 5 parts copper, 1 part tin for bells and cauldrons; 3:1 for spears and ceremonial weapons; 2:1 for mirrors, with lead added to enhance polish. For the tomb of a royal person, the system went into high gear. We learn this from the tomb of Fu Hao, official consort of the Shang king Wu Ding. Her tomb, one of the very few discovered intact, held nearly 500 bronze items, as well as more than 700 jades.

What about the Iron Age in ancient China? This began about 600–500 B.C., based on when iron objects appear in abundance. Several older relics, such as weapons dating from before 1000 B.C., have been found, implying trade with India and Central Asia introduced iron to China over time. The earliest iron objects clearly made in China used metal from meteors (easily identified by its nickel content). By the Warring States Period, however, smelting of iron ore was done on a significant scale to produce tools and some weapons.

At this time, Chinese artisans developed new systems to expand iron production greatly. Iron objects and smelter remains of the 5th century B.C. show that their kilns were able to reach blast furnace temperatures of perhaps 1200°C, something not achieved in Europe for another thousand years. Ironsmiths in China had already come to understand three key processes governing the making of usable iron. The first involves heating the ore to where nearly all unwanted material (slag) melts away. The second requires stripping oxygen from the raw ore (e.g. hematite, Fe_2O_3), which leaves behind the elemental iron and small amounts of silica (very high melting point). Smelting comprises both these processes. The third key process involves a certain amount of carbon from the kiln combustion gases combining with the iron to make iron carbide, Fe_3C, lowering the melting point. Chinese kilns were able to reach temperatures high enough to achieve all three processes.

Once melted, the iron can be poured into molds. But there are challenges: more than about ~2.5% carbon begins to make the final metal brittle. Pig iron,

Figure 6.8 A bronze ritual vessel, late Shang Dynasty (ca. 1300–1200 B.C.), known as Simuwu (for three characters inscribed on its underside). The vessel is the largest bronze thus far found in China. It stands 133 cm tall (52 inches) and weighs no less than 875 kg (1,925 lbs). It is estimated that 70–80 workers and craftsmen worked to produce it.

at 3.5–4.5%, is so brittle it will often shatter when hammered. Bloomery iron, at 2.5–4.3%, is a bit more usable but far from ideal. Cast iron, ranging from 2.1–4% carbon and 1–3% silicon, heated to a molten state, proved useful for many items, including weapons. As suggested by these concentrations, however, lower amounts of carbon (C) would be still better in many cases. Thus, the final process involved *removing* some of the absorbed C to specified levels. This requires oxidation – combining the C in the iron with O_2 in air, producing CO_2 given off as a gas. Chinese smiths discovered this could be done by reheating pig or bloomery iron in open-air conditions. They found that heating at 900–1,000°C for up to two days was needed for this to happen. Special furnaces, able to use bellows placed under vats for melting pig/bloomery iron had to be created. When the C content was lowered to 1–2%, the final product was steel, a particularly hard and durable form, excellent for many tools and weapons.

All of this, then, without the detailed chemistry of course, artisans in China figured out through experimentation and testing. The Han put such knowledge to use, not only for weapons, ritual objects, and tools but cooking utensils, building material, statues, and coins. Han rulers turned iron-making into a state enterprise, producing many thousands of tons every year. Private families were also allowed, for a time, to run many of the smelters and furnaces. This encouraged further technical advances, such as use of water wheels for the working of bellows to increase productivity.

Science in the Tang and Song Dynasties

Following centuries of conflict and division, Tang emperors brought an era of relative peace, prosperity, and cultural achievement that many scholars consider the high point of Chinese civilization. Certainly it was a time of impressive openness: traders, merchants, travelers, priests, intellectuals of all kinds were welcome in the capital, Chang'an, and mixed in its court. There was much interchange with Islam, Muslim settlements being established in China by the 8th century.

This was the era when printing and gunpowder were first developed into practical technologies. Books were now produced rapidly, abundantly, and cheaply. Many older texts, including scientific ones, were given official editions. Printed works helped strengthen higher learning, in part by providing many new textbooks. The government commissioned books on medical substances, including hundreds of plants, minerals, and animals, complete with illustrations and had some of these distributed to the public. Signs of a vital interest in nature appeared in the arts as well. Tang paintings (flower-and-bird images) show startling evidence of precise observation. Poetry, once again, made much use of natural detail, as shown by lines from "A Long Climb" by the famous Tu Fu: "In a sharp gale from the wide sky, apes are whimpering/Birds are flying homeward over the clear lake and white sand/Leaves are dropping down like the spray of a waterfall/While I watch the long river always rolling on."

Nearly all these trends culminated in the Song Dynasty, when Chinese science and technology truly flourished. To give some sense of this, we might list a few of the major advances:

- Dissection of human cadavers greatly aided anatomy. Drawings of the internal organs, adopted into work of the Persian-Jewish physician Rashid al-Din, were transmitted to Europe by the 14th century.

- Dissatisfaction with existing herbal remedies led to a government program, under the Board of the Grand Physician, to systematically test new medicines collected and submitted by provincial officials.
- Experimentation with, and successful development of, new strains of early-ripening, drought-resistant rice from Southeast Asia, coupled with improved methods of irrigation, caused crop yields to nearly double.
- Major advances in mechanization occurred, including intricate devices employing gear machinery and chain drives. These were used for astronomical instruments, a clock tower able to indicate time, date, season, and celestial movements, a carriage odometer, and spinning machines (with up to 32 spindles).
- New forms of mathematics, such as indeterminate analysis (solving n equations with $>n$ unknowns, and the incorporation of zero (from India).
- Advances in iron metallurgy involving redesign of blast furnaces and, due to deforestation, use of coal and coke (coal heated in an oxygen-poor kiln to drive off volatiles, leaving an almost pure carbon fuel) for more elevated temperatures. This greatly expanded the production of iron and steel, with impacts in tool-making, weapons, transport vehicles, ships, cooking, and more.
- Improvements in civil and hydraulic engineering, developed by analyzing problem situations, conceiving solutions, and testing them, possibly with the use of scale models. Invention of the pound lock for canals (an area between two sections of a lock where water is raised or lowered before the lock is opened, allowing for much safer passage of boats) greatly helped domestic transport and trade.
- Invention of the nautical compass, sounding ropes, and advances in shipbuilding, which placed Song China at the forefront of marine technology. For the compass, a thin, magnetized iron needle was balanced on a stem and encased in a small chamber with a glass cover, first used about 1115. Addition of stern-post rudders allowed for greatly improved steering and maneuverability of ships in open water.

An intriguing aspect to Song scientific culture was the mixture of traditional reverence for the past and a new ambition to go beyond it. This mixture did not happen by chance. Much interest and ambition in science came from the government, which embraced the power of technology. A distinct effort of the early Song court was to gather existing technical knowledge and make it widely available, creating a more informed public that would strengthen the state. Manuals on medicine and agricultural techniques, based on best practices from the past and present and simply written for a general audience, were distributed throughout the country. Stimulus for new ideas also came from expanded contacts with Muslim and Indian scientific cultures. A program for testing new drug remedies was inspired by Ibn Sina's *Canon of Medicine*, from which hundreds of new medicines were adopted by the end of the 11th century.

Printing and gunpowder: inventions of power

First mention of the printed page occurs in an imperial decree by the Sui Dynasty emperor Wen-ti, dated 593, commanding the printing of Buddhist images and portions of sutras. The technology existed already, therefore, used to decorate textiles and to produce personal and official seals. Thus, in its beginnings, printing in China was quite limited and evolved slowly over centuries. Only in the later Tang Dynasty did it become fairly common for longer texts and entire books to be printed, predominantly religious works. This pattern was changed by the imperial scholar, Feng Dao (882–954). In 932, he ordered the Confucian classics to be printed with expert commentaries, a monumental project that took 20 years and 130 volumes and exploded the use of print technology into other areas of writing.

The earliest printed texts were still produced as scrolls. The oldest surviving text bearing a date is the *Diamond Sutra*, produced on May 11, 868, and made from seven pieces of paper glued together to form a single sheet 4.9 m (16 ft) long and 26.7 cm (10.5 in.) wide. With an elaborate beginning illustration and characters that look caligraphic, this product appeared like a Buddhist manuscripts done by hand. Such was the case in other countries, too, including Europe, since handwritten manuscripts defined the "book" at the time.

The great innovation of the Song Dynasty was to reinvent the book as a codex – small rectangular sheets bound together along one edge and placed between covers – the book as we know it today. It is not clear if the Chinese invented this independently; the codex was in use for writing at the time of Julius Caesar and was adopted by Christians to produce early versions of the Bible. In China, the new form had many benefits. Printing presses could be smaller, cheaper, and faster. This led to an industry of private printers in many parts of China. Codex books were more portable, easy to store, and more convenient to read. Copies could be made more quickly, which helped the rapid dissemination of important works.

How were these print books made? Book-making was a professional craft with trained personnel and specialized tools, and it began with a calligrapher writing the text on a sheet of paper with a waxy coating to keep ink at the surface. This sheet was turned face down on a block of wood bearing a very thin layer of rice paste to hold the paper in place while absorbing enough ink to leave a clear impression. Once in place, the paper was rubbed evenly with a flat brush to ensure a uniform impression on the block. Next, the paper was carefully removed, and an engraver began to carve the characters into the wood with sharp metal tools. To reduce distractions (e.g. reading the text) and raise efficiency, characters were carved in parts: all vertical portions cut first, after which the block was rotated 90° and horizontal parts cut. Any chipped or broken characters were repaired with inlays. The block was then washed and, after drying, carefully inked with a brush. A sheet of paper was placed on the block and rubbed gently with a pad (not brush), requiring an experienced touch to prevent blotting, gaps, or smears. It was common for two facing pages to be printed at the same time from one long sheet. The sheet was then removed, allowed to dry, and inspected for any errors or problems. Sheets were folded in the middle and glued at the fold, then given a paper cover. If destined for wealthy buyers, special hard covers could be added. Such books opened from left to right.

Records from the Song Period say that a good journeyman printer could produce up to 2,000 double pages in a single day, if the blocks were complete. As many as 10,000–15,000 prints could be made from each block, possibly thousands more if it was refurbished. These are spectacular numbers, testifying to a surging demand for printed matter.

Yet the Chinese writing system seems to have worked against the next advance: moveable type. This was invented by a man named Bi Sheng about 1040, using moistened clay, from which component parts of characters were shaped and baked to hardness. Yet it did not take hold; neither did the innovation of using metal to form characters, which the Koreans introduced 200 years later. China continued to use woodblocks. The written language had a direct effect on the technology used to communicate it.

We come now to gunpowder. While there is a history of debate over its invention, whether this took place in India or China, scholarly consensus for the time being favors Tang Dynasty China. Earliest evidence of use is a painting from the famous Dunhuang caves, dated at around 950, that shows a demon holding a tube from which flames shoot out, a version of the "fire lance." This weapon, along with others, is described in the first work to contain actual formulae for gunpowder, the *Wujing Zongyao* ("Collection of Essential Military Techniques"), published in 1044.

Thus, by the early 10th century or before it was known that powerful incendiaries could be made by mixing three substances – charcoal, sulfur, and saltpeter (potassium nitrate; KNO_3), with the central role of saltpeter understood. There is a story that a Buddhist monk from Sogdia (Uzbekistan-Tajikistan), Chih Fa-Lin, visited Tang China and upon seeing saltpeter deposits growing in various places, expressed great surprise that the substance wasn't collected and used for alchemical purposes. When his companions did gather some and set it on fire, it produced great purple flames. The monk commented that it was indeed "a marvelous substance . . . and when the various minerals are brought into contact with it they are completely transmuted into liquid form." Chih Fa-Lin was speaking about the capability of nitric acid (HNO_3, known as "aqua fortis" in alchemy) to dissolve a great variety of substances. Starting with the 8th century Persian polymath Jabir ibn Hayyan (later known as "Gerber" in Europe), nitric acid was produced from a combination of saltpeter, alum, and Cyprus vitriol (copper sulfate; $CuSO_4$). This particular monk was thus bringing to China alchemical knowledge from Islam.

By the 11th century, the mixture of saltpeter, charcoal, and sulfur was being adapted to different uses. Formulae given by the *Wujing Zongyao* do not exceed 50% saltpeter, which is too low for explosives. Much testing (at times with unwanted results) revealed the full range of effects that could be produced, yielding four main insights: 1) different mixtures could create fires, explosions of varying power, or forces to propel a projectile with great velocity; 2) larger percentages of saltpeter created explosives; 3) desired effects could be made more reliable if the ingredients were crushed into powders, carefully mixed with a little water, then dried and ground up again; and 4) further improvement required that saltpeter be purified.

To understand these advances, we need to know the basic chemistry of gunpowder. Its effects are due to a highly accelerated form of combustion. Charcoal (mostly carbon) is the primary fuel, sulfur a secondary fuel whose real role is to lower the temperature at which ignition happens, while potassium nitrate is the oxidant, the substance that provides lots of oxygen and thus accelerates combustion. The basic chemical reaction can be written as follows:

$$2\ KNO_3 + S + 3\ C \rightarrow K_2S + N_2 + 3\ CO_2$$

However, charcoal is never pure carbon. It can be chemically summarized by the formula C_7H_4O. If we substitute this into the equation and balance both sides, we get:

$$4\ KNO_3 + C_7H_4O + 2\ S -> 2\ K_2S + 4\ CO_2 + 3\ CO + 2\ H_2O + 2\ N_2$$

This, too, is somewhat simplified (impurities create other products), but still revealing. It shows the reaction needs a large amount of potassium nitrate, compared to both charcoal and sulfur. Most of the reaction products are gases – it is the rapid transformation of solid material into these gases that creates the sudden expansion we experience as an explosion and that provides a propelling force.

Among the earliest military uses of gunpowder in the Tang and Five Dynasties (906–970) periods were arrows and spears carrying small packets of powder, lit by a fuse and intended to bring fire. An average mixture for this kind of use was 55% saltpeter, 25% charcoal, and 20% sulfur. At such levels, there is more than enough KNO_3 to produce a flash and flames. Military engineers already knew that raising the saltpeter amount to around 65% also greatly raised the explosiveness but this did not suit the purpose.

An idea for a new weapon arose: if a relatively small amount of "black powder" were confined in a tube and ignited, the resulting charge could send a projectile much further and faster than an arrow from a bow. At first, thick-walled bamboo was used for firing tubes, to send incendiary arrows and other projectiles – the fire lance. But bamboo soon failed under the temperatures and pressures generated, so metal came to be used. Some indication of how common this became is that upwards of 3,000 bronze and iron cannon were set on the Great Wall to repel the Mongols in the mid-13th century. Other explosive powders were now used to make types of grenades and bombs (hurled by catapults). In these weapons, the gunpowder would be mixed with iron fragments, pottery shards, even arrowheads, to create shrapnel. The mixture used for these explosives approximated that of modern gunpowder, averaging 75% saltpeter, 12–15% charcoal, and 10–13% sulfur.

A further advance came when engineers invented rockets. This was something altogether new, since these were self-propelled devices. To be reliable, with a linear trajectory, they required an exact balance of weight. This meant a uniform packing of gunpowder and a central channel to yield even thrust. Doubtless the results were variable at first. Yet a rocket could be fired a much greater distance and with explosive capability could provide a first line of attack beyond the range of all other weapons. As a technical achievement, the rocket can only be characterized as an example of engineering at its most brilliant under pressure.

Thus, we see an evolution from incendiary to explosive to propellant uses in gunpowder weapons. These innovations served the Song army well in a number of key battles against their northern enemies. But victory was short-lived. By the late 13th century, gunpowder no longer gave China an advantage. What happened?

The answer is clear: transfer of knowledge. In the new gunpowder era, knowledge was the greatest weapon of all. Like the Roman commander Marcellus, who wanted Archimedes captured alive, Mongol generals knew very well the value of Chinese engineers and their texts. Both were taken time and again during war with the Song, so that Kublai Khan's armies came to match the Chinese, weapon for weapon. It was the Mongols who created the first "gunpowder empire," whose other historical role was to transfer this knowledge westward, when some of their own engineers were captured by Islamic armies. In the brief period between 1240 and 1280, gunpowder technology came to be applied in Central Asia, Persia, large portions of the Islamic Middle East, and Europe as well.

Once in the hands of Islamic engineers, it was rapidly taken in new directions. By 1280, for example, a pivotal work (*The Book of Military Horsemanship and Ingenious War Devices*) by the Syrian author Hassan al-Rammah included no less than 107 different recipes for gunpowder (22 for rockets alone), and, more important, a reliable method for purifying potassium nitrate from saltpeter. Europe had not yet reached such a level. Ten years earlier, the English scholar Roger Bacon (1214–1294) had written in his work *Opus Majus* (1267) of the new explosive in the form of firecrackers: "that children's toy which is made in many parts of the world; a device no bigger than one's thumb . . . [yet from] the violence of that salt called saltpeter so horrible a sound is made by the bursting of a thing so small."

Shen Kuo: the enigma of genius

Over time, China had its share of brilliant thinkers but perhaps none so remarkable as Shen Kuo (1031–1095). A polymath who ventured widely and easily over every domain of knowledge, he has provided an iconic image of the cerebral heights reached under the Song Dynasty. Yet this most expansive mind of a brilliant age leaves us with profound questions.

Born in Hangzhou, Shen was educated at home (a common practice) and passed the imperial exams, placing into the highest cohort of scholars. He first worked on projects related to irrigation and flood control, where he was so successful that he gained notice from higher officials. He became an effective ambassador, military commander, Finance Minister, and chancellor of the esteemed Hanlin Academy, responsible for official interpretations of the Five Classics. He was also director of the Bureau of Astronomy, where he made important reforms: seeing that the bureau focused on calculation and largely ignored observation, he imposed a better balance in its work. Such varied effort required him to travel widely and to interact with a range of people from different social classes. A military debacle for which he was mistakenly blamed removed him from high office. Later pardoned, he spent the last years of his life on his estate, "Dream Brook," in study, contemplation, and writing.

During his lifetime, Shen Kuo wrote many works. Geographical atlases, treatises on music, military and legal matters, mathematical astronomy, medicine, literary and art criticism, and poetry all came from his hand. His final work, *Mengxi Bitan*, translated as *Dream Pool Essays* or *Brush Talks at Dream Brook*, gathered reflections about diverse subjects, including scientific ones. It is this volume that has drawn particular attention. Joseph Needham praised it as a "landmark in the history of science in China." And, indeed, among its many insights are: a description of the compass needle as showing both direction and declination; the idea that ancient relics must be studied in the context of their own time; accurate descriptions of meteorological phenomena (e.g. tornadoes); proper explanation of spherical planets, based on phases of the Moon; the idea of predator insects as a control on crop-eating insects; and invention of a superior ink using black soot from the burning of petroleum.

Such scope can only seem astonishing today. Aspects of biology, geology, physics, astronomy all seem to have been probed by Shen Kuo's indomitable curiosity. Yet the claim that this book represents a "landmark" in the history of science demands a closer look.

In truth, *Mengxi Bitan* is neither a scientific text nor a text about science. It is instead a collection of 609 brief essays, anecdotes, and meditations with a distinct literary flavor. These "jottings" (as they were called) are in a style that is lucid and simple, aimed at general readers, not scholars. The book is divided into 26 sections with titles like: "Crafts," "Human Affairs," "Literature and Language," "Divine Marvels," "Wit and Satire," and "Traditional Chinese Medicine." Most entries are told as stories, often with a moral. Some involve supernatural events. One essay describes an omen of hailstones "the size of eggs . . . all shaped like men's heads, with ears, eyes, mouths, and noses . . . very much like the heads of stone carvings." The *Book of Changes* is said to reveal "the universal law of nature" that living things are "always born upside down." Shen Kuo was a man of his time. Yet, in an essay on a meteor impact, he describes the fear and wonder of the local people, then turns to the recovered stone, noting it is "brown . . . like the color of iron, and its weight was similar to a piece of iron of the same size." That he has identified an iron-nickel meteorite seems beyond question and very impressive.

What of Shen Kuo's treatment of scientific subjects? These we would today place in a diversity of fields, as noted. Yet to call Shen Kuo a "geologist" or "botanist" makes little sense, though "astronomer" and "mathematician" do. Still, we are likely to be stunned at some of what he has to say. Taking geology as an example, he identified fossilized bamboo in rocks of the of Shaanxi area, where no bamboo grew, concluding that at some earlier time "the land was low and the atmosphere humid, suitable for bamboo." Similarly, he wrote:

> In the mountain passes there are frequently different kinds of shells and stones . . . spread across the rocks like belts. In former times, then, the seashore was there, although today the sea is some thousand *li* to the east. . . . In Shensi [Shaanxi] and westwards today the rivers flow . . . at no less than one hundred or more feet [above sea level]. All their mud that flows east year after year becomes earth of the great land.

Here are geologic truths that had to wait until the 19th century to be accepted in Europe. In just a few lines, Shen Kuo has expressed three fundamental ideas: that the Earth is dynamic, changing over time; that oceans once occupied the interior of continents; and that rivers continually deliver sediment to coasts, building the land seaward. He goes further when addressing why rock pillars exist in the canyons of Chekiang: "it is just that great waters [floods] have swirled about in the valley, taking away all the sand and earth and leaving only great rocks standing out high and solitary." The author rightly states, in a few words, the process and power of erosion.

To a geoscientist, it can be startling to see someone of the 11th century deducing so much that, in a later time, required long battles and libraries of evidence to become established in Europe. It makes us wonder what Shen Kuo might have seen on a field trip to the Himalayas.

In the end, however, little of this mattered. Shen Kuo's long-term effect on Chinese intellectual culture, especially through the *Mengxi Bitan*, was in the domain of literature. During the centuries that followed, he was read for his style and his commentary on art and writing; his geology was forgotten. In part, this had to do with the literary genre in which he wrote – the *biji*, or "notebook" style, a prose form that flourished in the Song Era. It comprised a miscellany of short pieces on diverse subjects, meant to appear casual, putting on display an author's broad knowledge and skill in a graceful but strategically entertaining style. The *biji* was excellent to set down memories and thoughts from a mobile life. It was no place for influential scientific work, which as shown by technical treatises of the time, required more detail and extended argument.

As historian Nathan Sivin has emphasized, a focus on Shen Kuo's scientific thinking tends to remove him from the larger context of his intellectual life. The Song Dynasty system of bringing scholarship into the service of the state and judging men of merit on the basis of their contributions to financial efficiency and military effectiveness, made it certain that a man of Shen Kuo's capabilities would be employed, as he was, in a range of useful, utilitarian positions, not as a thinker per se.

Concluding statement: on the writing of Chinese science

Cultural continuity in China, which most certainly includes its scientific culture, stretches back more than 5,000 years. Unlike India, whose stability was repeatedly interrupted by invasion and conquest, China remained largely intact until the 13th century, when the Mongols finally conquered the country (with the notable help of Chinese technology), yet were soon ejected by the Ming. Continuity helped China's scientific culture build upon itself until it reached unrivaled levels in the Song Era. This period was also a time of accelerated trade and intellectual exchange. Under the Song, we find an Islamic astronomer (Chinese name, Ma Yize) working in the Royal Bureau of Astronomy and the great mathematician Qin Juishao introducing use of the zero.

Such exchanges did not entirely stop with the Song or Yuan Dynasties. Nor did China's scientific culture enter into a long, dark era of decline. "Natural studies," meaning astronomy, calendar-making, medicine, among other subjects, were actually made part of the civil service examinations in Ming times. Publication of mathematical works, which had been largely forbidden under the Song for reasons of national security, was reopened by the Ming. Grouped under the larger rubric of "practical studies," these fields never rose to the status of the classics. Nor were they freed from the ascribed purpose of serving the state. Yet it was exactly this last factor, the perceived necessity to a successful imperial regime, that kept them active and advancing. Scientific knowledge from Europe, beginning with that introduced by the Jesuits, was, therefore, never swallowed whole but selectively nativized, mixed with Chinese scientific sensibilities, to create an amalgam.

The history of knowledge in any great civilization is never the isolated creation of one people. No less is this true for the history of science. Such scholarship is never the work of one individual. With regard to China in particular, Sir Joseph Needham (1900–1995) has been largely accorded for three-quarters of a century the role of principal historian for Chinese science. His major work, the extensive *Science and Civilization in China* series, whose first volume appeared in 1954, must be considered foundational to the entire field, especially in the West. Needham's service to the history of science is beyond all question or doubt.

Needham was an originator, doing battle against traditions of neglect. He sought to build a scholarly edifice so large and encompassing that the subject could never be denied its rightful importance again. In this, he succeeded. His work remains essential, and its contents are certainly represented in this chapter.

Yet, in some ways, this work has cast a brilliant shadow. There are a great many claims in it that Chinese scientists and inventors were "the first" to achieve some advance "centuries before Europe." We have included a few examples in this chapter to illustrate a point. Such has the ironic effect of holding up the West as the *de facto* standard for all comparisons, while turning the history of science into a tournament. Yet the most important aspect to any discovery is whether it influenced subsequent thought. In many cases discussed by Needham, this did not happen. Like Shen Kuo's insights about magnetic declination and erosional force, they were never pursued or expanded. This leads us to a second point. Because of its frequent claims for Chinese superiority, Needham's work has a political dimension, one that has proven useful to those with non-scholarly motives.

Needham's writings, therefore, need to be viewed as a beginning, not a canonical end. They provide a necessary starting point, with gaps and flaws like any such effort. Some of his conclusions regarding priority for certain discoveries may even need to be reexamined. But this is what good scholarship does. It takes a stand, while also suggesting that the same ground be walked again, with different eyes and newer tools.

This returns us to Marco Polo. His book, with its mixture of credible and incredible reporting, provides evidence for the idea that the writing of history is itself a form of travel. "You may take it for a fact," says the narrator of the prologue, that for all the years he stayed in China, Marco Polo "never ceased to travel on special missions. For the Great Khan, seeing that Messr Marco brought him such news from every country . . . used to entrust him will all the most interesting and distant missions . . . This, then, is how it came about that Messer Marco observed more of the peculiarities of this part of the world than any other man. . . ."

Notes

1 This does not include the very large and ancient literature dealing with magic squares and other types of numerology. The Chinese fascination with numbers runs very deep, and its link to divination, prediction, and much more began well before the *I Ching*. This chapter does not take up this subject, as it was less central to science. Interested readers might consult the excellent discussion by G. G. Joseph in his book *Crest of the Peacock*.

2 In modern terms, the Rule of Three utilizes basic algebra. It can be described as follows: given three numbers of known value, a, b, and c, we can find an unknown, d, when $a/b = c/d$, if we cross-multiply (to get $ad = bc$) and then divide the right-hand side by a, to produce $d = bc/a$.

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7 Science in Islam

Absorption and transformation

> The intellectual sciences are natural to man, inasmuch as he is a thinking being. They are not restricted to any particular religious group. They are studied by the people of all religious groups who are all equally qualified to learn them and to do research in them. They have existed (and been known) to the human species since civilization had its beginning in the world.
>
> Ibn Khaldun, *The Muqaddimah*

Jafar Abdullah al-Mansur became caliph of the world's greatest empire in 754 C.E., roughly a century after the death of the Prophet Mohammed. One of his first decisions was to move the capital. "We Abbasids are a recent dynasty," he said. "We have supplanted the Umayyads, but we cannot be safe in their Syrian capital, Damascus. We must move closer to the Persian source of our power." Thus did the city of Baghdad begin.

Al-Mansur's idea was not to find a new capital but to build one – a new city of magnificence. It would be near Ctesiphon, Persia's own hub, a crossroads for routes to the Mediterranean, Arabia, India, the Silk Road. An imperial capital close by would soon absorb all this internationalism and wealth. It would outshine every city of the Umayyads. It would reassure non-Arab peoples, the Jews, Christians, Zoroastrians, and Persian Muslims, that they too were now members of greater Islam.

After scouting the area, al-Mansur chose a small settlement where the Euphrates closely approaches the Tigris from the west and the Diyala River bends to meet it from the east. A network of canals sloping gently from the Euphrates to the Tigris fed an irrigation system that made the land green. Nestorian monks who ran a monastery nearby told the caliph that cool evening breezes kept away the mosquitoes, otherwise relentless. People had lived here for a thousand years (brickwork that would be found in the 1800s bears the name of Nebuchadnezzar II, Assyrian ruler of the 6th century B.C.). The name "Baghdad" was itself ancient, derived from two old Persian words, *Bagh*, meaning "God," and *Dddh*, signifying "founded."

Plans for the new city were laid. Al-Mansur's court astrologer Nawbakht the Persian identified July 31, 762 at 2:40 p.m. the time for ground-breaking. The core of the city would be a great circle, like a radiating sun, and would serve as the nucleus for suburbs and markets. We are told by the geographer Ya'qubi that al-Mansur

> assembled engineers, men with a reputation in the art of construction, and surveyors skillful in measuring lengths and surfaces and in dividing up land in order to draw up the plans of the capital. . . . When all the workers that he had called arrived, the masons, the woodworkers, the carpenters, the black-smiths, the laborers, he distributed payment in kind and determined salaries.

This author, who lived a century later, tells us that al-Mansur wished to picture what his new city would look like, so he ordered its full outline to be drawn using ashes. After walking through its gates and courtyards, he commanded that cotton seeds be placed over the ash outline, oil poured over them, and the whole lit with fire. A great illuminated circle, flaming in the desert night, appeared. The caliph was satisfied. As the circle was the most perfect of forms, including those of the heavens, so would Baghdad be the most celestial of cities, a new center of faith, power, and knowledge for the world.

Background

Baghdad did indeed become such a center. Many legends grew about it, especially after its destruction by the Mongols in 1258. There are other tales as well, such as one told many times in the pages of both scholarly and popular books, in classrooms and lectures about the history of Islam and medieval science.

This story begins with the fall of Rome, when Greek science passed to Nestorian Christians, who were persecuted and driven out of Constantinople, settling in areas to the south and east. Here, they took up the Syriac language, preserving this science in a new tongue. Two centuries later, Muslim armies conquered the region. Between the 8th and 10th centuries, this science, plus a few texts from Persia and India, were translated into Arabic and thus preserved anew in Islam. The Arabs had no scientific culture of their own to speak of and so made Greek knowledge their own. Thus it was saved until it could be translated into Latin and transferred to Europe, its true and original home.

It is a story of drama, therefore. The only problem being that, beyond the broadest outlines, it is almost entirely false.

Nestorian scholars, first of all, were more than merely preservers of Hellenistic science. They and other knowledgeable non-Muslims were essential actors, working as translators, interpreters, teachers, and mentors. Almost certainly this was true for scholars of Hindu science too – Hindu numerals, the sine function, and the zero all entered Islamic intellectual culture in the 800s. Our story above also makes no mention of Islam's debt to China. Paper arrived as early as the 8th century, while gunpowder and the compass were introduced in the 1200s. Then there is the matter of what Muslim thinkers *did* with the material they acquired. Simply preserving ancient knowledge would never have brought Islam a "golden age."

Instead, this new knowledge was critiqued, edited, corrected, and updated, after which Muslim thinkers pursued their own investigations beyond what the Greeks and Hindus had achieved. It was this more advanced textual treasury, combined with what had come from China, that eventually entered Europe.

There is one other "small" problem with the traditional story. Did the Arabs really lack *all* science before the rise of Islam? If so, how could they ever have understood a work as complex as Ptolemy's *Almagest* or Euclid's *Elements*? Most of the Arabian Peninsula, with its vast deserts, was never conquered by either the Romans or Sassanid Empire. It had its own ancient civilization, which had traded with Sumer and Egypt. In the centuries before Mohammed, it was crossed by trade routes from the Persian capital at Ctesiphon to Medina and Mecca more than a thousand kilometers away in the Hejaz region bordering the Red Sea. On the eastern side, Arabia was home to Christians, Jews, Zoroastrians and to a host of languages including Aramaic, Syriac, Persian, and Arabic.

The Arabs, in short, were anything but a scattering of tribes living a Paleolithic existence in unrelieved isolation. They had an astronomy, iron metallurgy, knowledge of gems, medicines, textiles. They had their own understanding of nature, enhanced by what they had absorbed from the scientific cultures with which they were in contact. And what of the knowledge needed to live in the desert? Understanding of oases, including the quality of their waters, where wells could be dug, their ecology, were all needed. Thorough knowledge of the camel, its anatomy, behavior, diseases, was also present. Nomadic Bedouin had an intimate familiarity with desert landforms, how wind shaped the dunes and how these migrated, where they were firm enough to support a caravan's weight, where water might be found after a rare rainfall.

No less, pre-Islamic Arabs had a system for reading the heavens, generally known as *al-anwa'*. This is often referred to as "folk astronomy" or "star lore," since it was largely polytheistic and oral, until later recorded in books by Muslim scholars. Such terms, however, suggest it had no scientific value. But like many early peoples, the pre-Islamic Arabs used a lunar calendar for marking the seasons. *Al-anwa'* included constellations along the ecliptic associated with the 28 lunar stations of Hindu astronomy. These stations and the risings and settings of particular stars were central to early Arabian culture, as they were used to determine the seasons, predict weather patterns, fix the timing of various rituals, and, of course, guide travel at night. A fair portion of these asterisms continued to be used in the early Islamic period, and some *anwa'* names found their way to Europe and survive to the present, as we will see.

Islam, as a new world religion, rose very rapidly (Figure 7.1). Culturally, it took longer to coalesce, embracing as it did a diversity of nations. Its origins were with the Prophet Mohammed and his followers in the Hejaz. He was born in 570 to a prominent tribe in Mecca and became a camel driver and later a manager of caravans. On his many trips between Arabia and Syria, he came in contact with Jews, Christians, Zoroastrians, thus people of other faiths and ethnicities. According to Islamic tradition, when he was 40, he was visited by the angel Gabriel, who gave him the message to preach to his countrymen and to others the message of

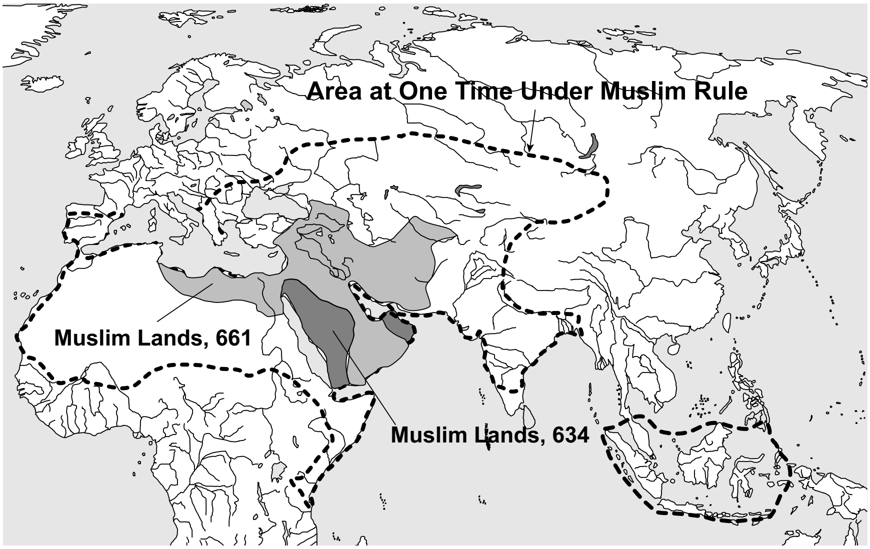


Figure 7.1 Map showing extent of Islamic Empire in 634 (two years after the death of Mohammed), in 661 (after the first four caliphs), and in its maximum combined extent.

a new religion of "Islam" ("submission" to the word of Allah). Mecca at this time was not only a hub of trade but also a site of worship for various tribes that had built sanctuaries there, especially within the Ka'aba – an ancient building in the shape of a cube, containing a sacred black stone, each of its corners aligned with one of the four cardinal directions. Mohammed's preachings led to his persecution, and in 622, he left with his followers for the city of Yathrib, 350 km to the north, where he was warmly welcomed, gaining many converts. Within six years, the city had become Muslim, resisted large attacks by armies from Mecca, which finally surrendered to the Prophet. Yathrib was renamed *Medinat al-Nabi*, "City of the Prophet," and eventually Medina. The Islamic calendar begins with Mohammed's journey to this city.

During this time, Mohammed continued to have revelations. Though most likely literate to some degree, he seems to have dictated his visions to certain of his followers who either wrote them down or passed them on to others who were able to do so. After Mohammed's death in 632, these writings were gathered to form the Qur'an (lit. "recitation"), the holy book of Islam. By this time, the religion had spread over most of Arabia and effectively unified its tribes in a single religious-political state. Its rapid spread beyond Arabia, both to the west and, especially, to the east, was spectacular and brought many challenges to creating a unified religious culture.

Islam's greatest prize by far, however, was not the huge territory it had overrun but the unparalleled intellectual riches it now possessed. These included the manuscripts and knowledge of the Nestorians, the Byzantines, the Persians themselves – meaning those stored and copied in the great cultural centers along the western Silk Road – and finally those of the Hindus in western India. As noted, it would take centuries of translation, retranslation, study, teaching, and writing to absorb the greater part of these riches. It was an intellectual challenge as great as any ever faced by a civilization.

We can see how well they met this challenge by consulting our own language. In English, we find a dictionary of words – many related to the sciences – that have come from Arabic: adobe, alchemy, alcohol, algebra, algorithm, alkali, azimuth, benzene, borax, camphor, carat, cotton, elixir, erg, gazelle, guitar, hashish, hazard, magazine, marcasite, muslin, nadir, orange, ream, sabkha, sofa, talc, tamarind, tariff, zenith.

Intellectual setting of Islamic science

Muslim armies by the middle of the 8th century had largely taken command over three ancient civilizations: Egypt, Mesopotamia, and western India. Conquered as well were the cities of Iraq and Syria, where Greek scientific and philosophical works were still taught in some form. Not since Alexander the Great, whose deeds were well-known to Islam's rulers and generals, had an empire uniting so many peoples and cultures existed.

Intellectual wealth, however, could not be absorbed by simple possession. It required cultural openness, scholarly ambitions, and also Islam itself, as a religion. This last point cannot be dismissed or ignored, though it can be exaggerated.

Islamic scholars were interested in the natural world for a number of reasons. Some were practical, related to such things as calendar-making, medicines and healing, and the forecasting of future events. Another motivation was the need to determine times of daily prayer, requiring astronomical and mathematical knowledge, and also what is known as *qibla,* the direction to the Ka'aba in Mecca that must be faced for prayer. As described, the Ka'aba is central to Islamic worship, lying within the religion's most sacred mosque, the Al-Masjid al-Haram, and thus forming a geographic point on Earth to which all Muslims are attached. During the yearly pilgrimage, called the *hajj*, millions of worshippers circle the mosque and the Ka'aba itself (Figure 7.2).

Also important, however, was the perception on the part of rulers that a number of non-Arab cultures, though conquered, were in possession of knowledge that made their societies more sophisticated. This was especially true of Persian culture, which drew more heavily on India than Greece for its astrology, which became the first area of great interest by Muslim caliphs. Astrology, however, gave rise to many questions about the nature of the heavens and the patterns of their movements. It became apparent that key astrological texts had been written in Greek, as well as Pahlavi (early medieval Persian) and Sanskrit. Regarding the Greeks, whose science they came to especially favor, Islamic intellectuals realized it was rooted in a philosophical outlook concentrated above all in the works of Aristotle. Their translation of ΦλοσοΦα (*philosophia*) was *falsafa*, which included both scientific and philosophical knowledge.

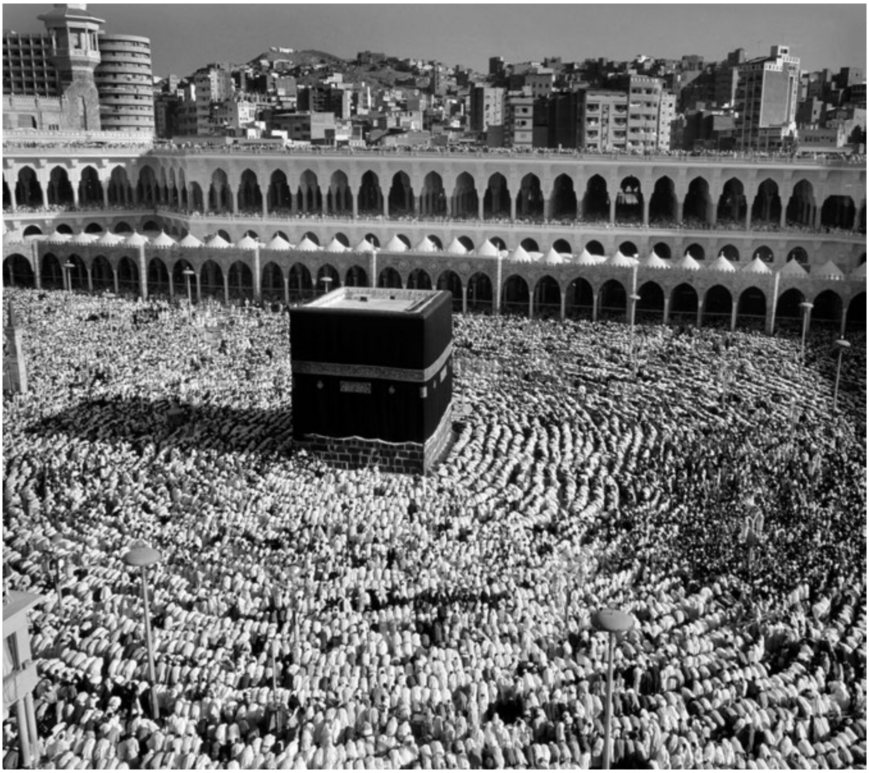


Figure 7.2 Pilgrims praying facing Ka'aba, Mecca. © Art Directors & TRIP/Alamy.

In this regard, we should avoid the error of thinking that Greek, Persian, and Hindu elements were somehow foreign to Islam. True, this is how they came to be regarded by conservative Muslim thinkers, who felt that *falsafa* was not needed, since all knowledge useful and native to Islam was in the Qur'an, hadith and the sunnah (the teachings and practices of the Prophet Mohammed). Yet, as historians have said, *falsafa* belonged to peoples who were all part of Islamic civilization.

It is essential to understand, too, the power of the Qur'an. As a "religion of the book" whose words needed to be memorized, Islam demanded the spread of literacy, especially in Arabic. With a standardized version of the Qur'an created by the mid-7th century, this growth in literacy became easier, having a consistent text. There were soon other works of value, both religious and non, with poetry having much favor. Booksellers were among the only merchants allowed to set up shop adjacent the mosques, reflecting the special dignity and worth given to literacy. Expansion of the empire made Arabic the language of power, of government, the military, institutional religion. In time, it took over trade, education, and scholarship. While there was resistance among Persians toward giving up their own tongue in matters of authority, a sizeable number of them, especially scholars, became bilingual or proficient in Arabic by the 9th century.

The beginnings of translation came in the early 8th century, after the empire had been extended across Egypt, the Middle East, and as far as the Indus Valley (see Figure 7.1). Early translation only evolved into a full-scale movement with rise of the Abbasid Caliphate after 750. The Abbasids were Arabs, descended from the Prophet Mohammed through one of his uncles, who had been forced to flee by the Umayyads to the Khorasan region of Persia, where they gained a powerful following and a deep appreciation for the cosmopolitan Persian culture, including its science. After their victory over the Umayyads, they turned to the newly converted Persians for their model of government, for administrators in their ruling bureaucracy, and for examples of intellectual culture.

Important as they were, the Abbasids were not entirely responsible for Islam's intellectual rise everywhere. They lost control over the westernmost portion of the empire, which established a separate caliphate in Spain, with Cordoba as its capital. Al-Andalus, as Muslim Spain was known, came to be a separate center of scientific translation, teaching, and writing, particularly in the 10th–12th centuries, and involved Jewish and Christian scholars as well.

In the main empire, meanwhile, an essential element regarding the growth of interest in science was the Mutazili theology. This school emerged in the late 7th–early 8th century out of disputes regarding the nature of God and the Qur'an, the question of free will, and the place of reason and revelation. Mutazilites held that people are indeed responsible for their actions, and, more important, that the Qur'an was created and is not eternal and continuous with God, who is perfect in and of Himself. From this, it followed that an understanding of God's demands and His divine plan can be attained both through reason and revelation. Reason, therefore, becomes an essential aspect of belief, a way to comprehend the world and God's message in it. The 12th century Muslim historian of religion ash-Shahrastani, in his *Book of Creeds and Sects*, described Mutazilite rationalism in this way: "All objects of knowledge fall under the supervision of reason and receive their obligatory power from rational insight."

At the same time, however, Mutazilite thought held a conflicted place in Islamic culture. Never fully accepted by a majority of Muslims, it was directly opposed by many traditional clerics and hadith scholars, who saw reason and philosophy (especially that of the Greeks) as incompatible with primacy of the Qur'an and unquestioning devotion to God's will. In this view, Greek, Persian, and Hindu science was innately foreign to Islam. Thus, even the best efforts made by devout thinkers to reconcile the conflicting theologies never wholly succeeded.

Translation movement

Knowledge is a mobile form of culture. With very few exceptions, it has never belonged to a single people for very long. We have spoken of how the Greeks "borrowed" and "adopted" – two euphemisms for translation – material from Egypt and Mesopotamia. In neither of these cases, however, was there a massive program that came to be underwritten by government and a large part of society, all at once. Such is what took place the 8th and 10th centuries in Islam.

As noted, certain Syriac and Persian works first began to appear in Arabic under the Umayyads in the early 8th century. For practical reasons, works in astrology (predicting future events), astronomy (calendar-making), alchemy, and medicine were translated from Syriac into Arabic and from Hindi into Pahlavi, and then Arabic. The Umayyad prince Khalid ibn Yazid (d. 704), a highly educated and accomplished person, seems to have been the first royal authority to order translations of particular books. Umayyad caliphs and scholars in their court were quite interested in the ability of Christian clerics to argue a point of view skillfully, using logic and styles of rhetoric. Thus, a desire also grew for books that taught related subjects. Overall, translation was already becoming a cultural force by the time it was accelerated under the early Abbasid caliphs.

Translation was central to Islam's "golden age" in science. By any account, translating works like Ptolemy's *Almagest* (whose title is Arabic) or Brahmagupta's *Siddhanta* was essential scientific work, not a support for it. What, then, were the major features of this movement and its history? Here are the main ones:

- Beginning with al-Mansur, translation of scientific works became a full-scale movement. Support came from many levels of society and involved political, economic, scholarly, institutional, and status elements. Multilingual individuals involved in translation were highly valued and well-paid. Such was the mark of an openness to cosmopolitanism and the larger world.
- The movement was in no way accidental. It was born from an active, even urgent, desire on the part of Islamic thinkers to search out and find the most advanced knowledge of the natural world. Thus, it is wrong to speak of Islam as "inheriting" Greek, Persian, and Hindu texts. They took possession of them.
- The movement overflowed boundaries of religion, background, social position, and political affiliation. Translators included not just Muslims, but Christians, Jews, and Persians who did not convert to Islam. Hindu and Chinese scholars, engineers, and officials were involved at different times. This pluricultural aspect was also typical for the translation work itself, which was often done by two individuals or teams, e.g. one person or team bringing a Greek work into Syriac, another into Arabic.
- From the 9th century, many translators became researchers as well, adding original work to the growing scientific culture. This was particularly true of Persian scientists, such as al-Kwarizimi, Ibn Sina, al-Razi, and al-Biruni. The "golden age" of Islamic science was not limited to any group. Greek science did not "pass to the Arabs" alone, but to Persians, Sabians, Copts, and others as well.
- Translation was selective, focused on scientific and related philosophical works. It did not transfer "the Greek heritage" to Islam, because it ignored nearly all of Greek poetry, drama, histories, travel writing, discussions of art, and more. Also, only part of Greek philosophy was chosen, dominated by Aristotle.

- The most influential texts were translated multiple times and edited into newer versions as well. More than a few were adapted and paraphrased rather than actually translated. In part, this reflects a perceived need for useful renditions. But it also shows an interesting aspect to the overall historical process, which involved turning Greek and Syriac works into those that were specifically Muslim (Figure 7.3).
- Translation was institutionalized in several ways. Well-known scholars set up their own workshops, with several or more translators and assistants. Some worked individually for wealthy patrons or royal officials. A few seem to have had freelance careers, at least for a while. By far the most productive institution was the *bayt-al-hikma,* or House of Wisdom, a facility built and supported by Abbasid caliphs that combined the functions of a translation center, library, training complex, and institute for advanced studies.
- Starting in the 9th century, translation was greatly aided by a powerful innovation: paper mills. The first such mill was built in Samarkand (Uzbekistan), following the Abbasid victory over the Chinese at the Battle of Talas in 751.

Figure 7.3 Image of Aristotle teaching his students a lesson on the astrolabe, as portrayed in a 13th century Turkish miniature (illustrated book). We should note here the adaptation. Instead of walking through the grounds of the Lyceum, lecturing as he actually did, Aristotle is shown dressed as an aged Muslim teacher, who instructs while seated on a divan, his students on the floor before him. © The Art Archive/Alamy.

Prisoners of war included engineers or craftsmen familiar with the process of paper-making. Before 800, water-powered pulp mills were in operation at Baghdad, yielding mass production of paper, replacing the use of parchment and papyrus.

- The movement followed an overall evolution, beginning with translations that were often literal and variable in quality (8th–early 9th c.), since the knowledge was new and demanded many new Arabic terms. Later versions were much better and were used to produce summaries and other introductory texts for teaching and study (9th c.). Overlapping this and continuing afterward, Islamic thinkers performed their own observations and experiments and became sometime critics of errors and other material in translated texts (9th–13th c.).
- The main part of the movement lasted until the late 10th century. Its falling off was a result not of any decline in the need for these texts but rather that they had become fairly standardized as basic material for learning and study. Scientific activity had by this time evolved toward new, original work by Islamic thinkers. It had evolved, that is, from translation to authorship and advancement.

House of Wisdom

The *bayt-al-hikma* was established in Baghdad by Harun al-Rashid (ruled 786–809), the fifth Abbasid caliph. So much is known. However, we are still lacking in many details about the exact nature of this institution. The idea that it combined the work of translation, training, mentoring, research, and publication – in effect, a modern research institute – has been exciting to many scholars and authors. But the historical record remains thin. It can be said to permit generous interpretations but also the call for strict caution. In what follows, then, we will treat the *bayt-al-hikma* with a degree of both generosity and caution, while understanding that it has come to serve as a kind of historical marker of its own.

The true origins of this institution may have begun during the reign of al-Mansur, who was eager to adopt Persian examples. Under al-Rashid, however, whose magnificent court forms the background for *A Thousand and One Nights*, it emerged as a named and recognized institution. It was under al-Rashid, in 809, that the first true hospital was built in Islam, in part based on knowledge acquired from translations of Galen and Hippocrates. Hospitals soon were erected in every major city of the empire, where they did not already exist. As for the *bayt-al-hikma*, its final maturation came about during the rule of al-Rashid's son, al-Mamun (ruled 813–833). There is a famous story that tells of a dream al-Mamun had while visiting the ancient Silk Road city of Merv. In this dream, the caliph found himself standing before Aristotle, of whom he asks: "What is the good?" He received the reply: "Whatever is good according to intellect." From this, the caliph reputedly understood that knowledge of the external world and a devout life in Islam were not in conflict; one would aid the other.

Al-Mamun had been raised and educated in the midst of translated knowledge, especially that of Greek and Persian authors. His tutor, the Persian Ja'far, gave him a deep love of books, such that he often demanded them (rather than gold) as tribute from rulers he had defeated. He sent emissaries to Constantinople requesting the use of old manuscripts in Greek. And he apparently sent others to collect scientific works from existing Persian and Hindu libraries as well. Inspired, perhaps, by the Great Library at Alexandria, he seems to have been eager to assemble a great collection of scientific, medical, and philosophical works and to have them translated into Arabic. By the time of his reign, there were probably many private libraries in Baghdad, as well as in Basra and Damascus. The ambition to create a library on a scale like that of Alexandria would make knowledge a living treasury, a source of advancement and power as well as learning and study.

Blended with Mutazilite views about the nature of faith and God, this kind of motive stimulated what has been called a humanistic outlook, focused on human capabilities for understanding and belief. Though he had to deal with much rebellion and strife during his reign, as well as conflict with Byzantium, al-Mamun turned Baghdad into an intellectual center of the highest order. Indeed, it was under al-Mamun that the pattern was established for scholars from all corners of the empire to seek work and success in such centers, which later came to include other cities, such as Cordova (Spain) and Cairo.

Yet the *bayt-al-hikma* remained a special institution in some ways. It was associated with setting professional standards for translation, mainly through the high-quality work of Hunayn ibn Ishaq (809–877) and his students. Hunayn was a Nestorian physician, born in Al-Hira, Iraq, who learned Syriac and Arabic as a child and may have mastered Greek as an adult. Working alone, with his son, Ishaq, and with other assistants, he translated an enormous number of works, including many medical treatises by Galen. He traveled a good deal in search of Greek manuscripts and, whenever possible, would acquire more than one copy of a given text in order to assemble the best version for translating. He gained fame as well for his excellent style, which may well have improved his sources. No less was Hunayn the author of original works on medical topics. His book *Ten Treatises on Ophthalmology* is a tour de force of eye anatomy, disease, and treatment, including surgery, and remained a standard text into the 13th century. Another work, *Introduction to the Healing Arts*, became a widely used text in medical training and was translated into Latin, becoming a reference for European physicians in the 15th and 16th centuries.

An important aspect of the *bayt-al-hikma* involved attracting scholars from many parts of the empire. Three brothers associated with the institution who acted as both patrons and authors were the Banu Musa, Persian sons of a court astrologer/astronomer for young al-Mamun who took charge of the three boys' education after their father died. Favored in the court of al-Mamun, the Banu Musa provided funds to pay translators, journeyed to find Greek manuscripts, and also recruited new translators, such as Thabit ibn Qurra, a Sabian from Harran (southern Anatolia), who would come to be one of the most accomplished scientists in Islam. Also from Persia was the mathematician and astronomer al-Khwarizmi

(c. 780–850), whose books would introduce Hindu numerals and create the field of algebra. Yet another important thinker attached to the *bayt-al-hikma* was the polymath – the first of many in Islam – al-Kindi (801–873). Born in Basra, al-Kindi came to be known as "the Philosopher of the Arabs" for reconciling Aristotle's philosophy with the Muslim faith, including revelation. As we will see below, however, al-Kindi served a larger intellectual purpose, writing an entire shelf of books introducing Arabic readers to many subjects in Greek and Hindu science and philosophy.

After the reign of al-Mamun, the *bayt-al-hikma* continued to be supported by the next caliphs, al-Mu'tasim (ruled 833–842) and his son, al-Wathiq (r. 842–847). But when al-Mutawakkil came to the throne in 847, things began to change. More religiously conservative than his predecessors, he reduced freedoms for non-Muslims, had their churches and temples destroyed, and forbade them from holding most government offices. He was assassinated in 861, an act that kindled a period of instability, violence, and intolerance. Though the *bayt-al-hikma* survived this period, it suffered a long, slow decline thereafter, until finally destroyed, along with Baghdad itself, by the Mongols in 1258.

Islamic astronomy

Knowledge of the heavens began and remained a particular focus of early Islamic science. One reason for this was the importance the stars and planets long held for the Arabs but also all the peoples who were eventually embraced by the empire. Astrology had a central place in Persian, Hindu, and Greek society and government, as well as that of Egypt and Mesopotamia, and, in its Persian form, was adopted by much of Islamic society. Yet many Muslim astronomers who pursued mathematical astronomy came to disparage astrology as unimportant compared with geometric study of celestial motion.

Such study was never far removed from religious needs. Islamic holy days needed to be predicted and this was complicated since the month does not begin with the new moon but instead the first crescent (the symbol of Islam itself). Forecasting exactly when the crescent would become visible was a challenging problem. Most important, however, was determining the *qibla*. As the empire expanded to distant realms in Persia and North Africa, not to say Spain and India, determining the correct direction of Mecca for the orientation of all mosques and for prayer became a crucial task. It remained one of the more sophisticated challenges in mathematical astronomy for more than two centuries. Many attempts at providing solutions, both exact and approximate, were made, using spherical trigonometry or orthogonal projection. Why was this true? Without a standardized map of the Earth, showing latitude and longitude, the precise location of cities in relation to each other was difficult to determine and required the use of complex geometric relationships. Once achieved by mathematical astronomy, the method revealed that a number of early mosques were, in fact, misaligned. Some of these were rebuilt; others, however, erected by companions of the Prophet Mohammed, were left alone.

Several trends can be seen in the development of Islamic astronomy. The first involved absorbing the knowledge of Greek and Hindu authors, therefore creating a whole new realm of understanding and terminology. This included the writing of epitomes (summaries for study), such as those by al-Fahghani and al-Kindi, two great polymaths. By the early 9th century, the key text for serious astronomers was designated as Ptolemy's *Almagest* – a book we know today from its Arabic name, *Kitab al-Magesti* ("The Greatest Book") but which Ptolemy himself had titled *Mathematike Syntaxis* ("Mathematical Treatise"). Yet other works, such as the *siddhanta* texts of Aryabhata and Brahmagupta, as well as Ptolemy's own *Handy Tables* – a highly useful manual for computing celestial positions, plus lunar and solar eclipses – made clear the importance of direct observation. When Ptolemy's own methods were used for this purpose, star positions did not correspond to those in his books, written more than 600 years earlier. This led to work focused on correcting such measurements, work that utilized new observatories that the caliph al-Mamun ordered built for the purpose.

The *Handy Tables* became the model for a type of Arabic astronomical table called a *zij* (Persian for "thread"). This presented numerical data adopted from Ptolemy and from Hindu *siddhanta* but later included computations from Islamic astronomers based on their own observations. Some *zij* were translated into Latin and had a major impact in Europe, starting in the 12th century.

If we consider the long history of pre-modern astronomy, we can only conclude that Muslim astronomers brought things to a new level. Yes, they remained bound to the geocentric view of the universe. Though they knew of Aryabhata's work, they rejected any idea that the Earth rotated. Yet, though bound to it, they were the first to critique and correct the Ptolemaic system. We could say, in fact, Muslim scientists both elevated Ptolemy and returned him to ground. This proved to later astronomers in Europe that even the most sophisticated system for keeping the Earth at the center was flawed.

We cannot leave this subject, however, without recognizing another kind of influence. Perhaps the most beautiful work of Islamic astronomy was the *Book of the Fixed Stars* (*Kitab Suwar al Kawakib*, c. 964) by the Persian astronomer al-Sufi bearing separate entries on the 48 constellations described by Ptolemy with wonderful illustrations (Figure 7.4). Al-Sufi came from Isfahan, which had its own school of astronomy. *Book of the Fixed Stars*, in fact, was a brilliant creation. While accepting the Greek constellations, it added some Arabic asterisms and replaced a number of star names with Arabic ones dating from the period of *anwa'*. It also updated star positions from Ptolemy's time. Such a merger of Greek and Arab influences was no less apparent in the images, which portray Greek mythic figures in Muslim dress (Figure 7.4). Each image, moreover, was shown twice, one showing how it appears from Earth, the other on a celestial globe from the "outside." Al-Sufi's work is also the oldest known that records and illustrates the observation of "little clouds" (nebula) that, in fact, are other galaxies (Andromeda and Large Magellanic Cloud). Using a translation of this work along with the star catalogue of the *Almagest*, the German Johann Bayer created his own magnificently illustrated

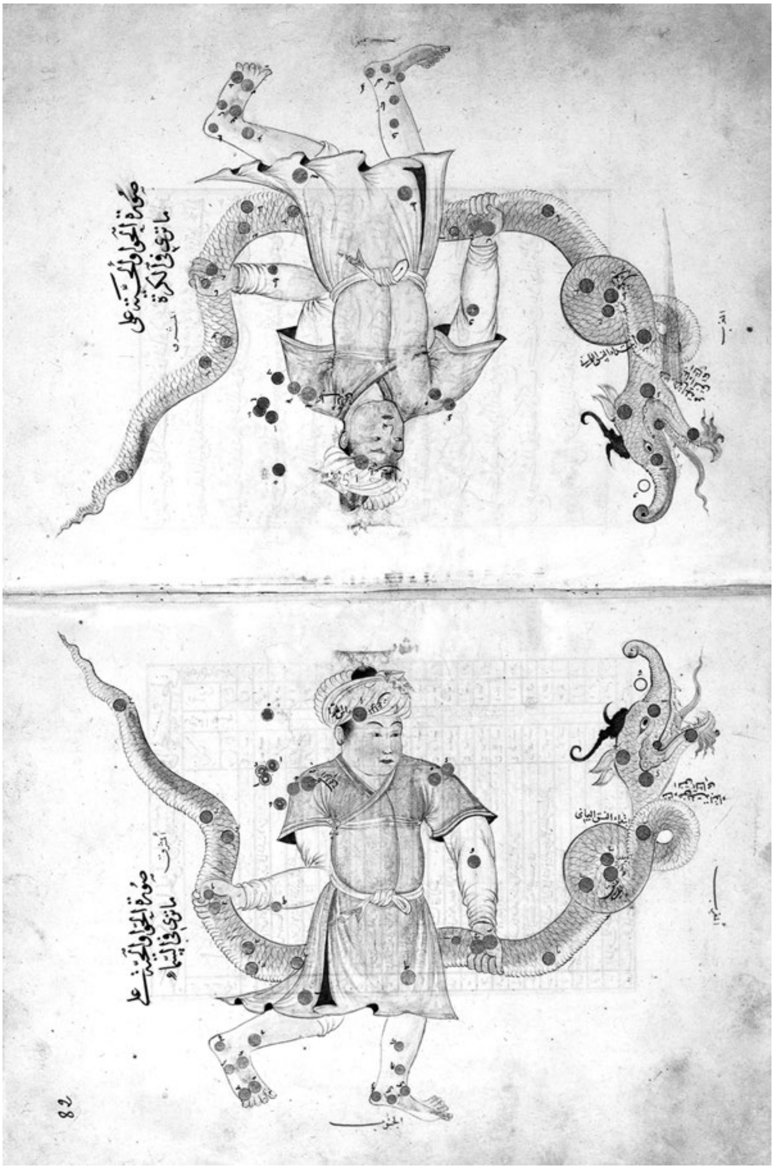


Figure 7.4 The Greek constellation Ophiucus ("serpent-bearer"), portrayed in Persian garb, from the *Book of the Fixed Stars* by al-Sufi, Arabic manuscript of 11th century. © De Agostini/Getty Images.

celestial atlas, *Uranometria*. In so doing, he adopted an impressive number of al-Sufi's star names: Acrab, Aldebaran, Algol, Altair, Betelgeuse, Deneb, Homam, Pherkad, and Rigel, which we use today. In linguistic terms, the heavens speak to us in a number of tongues, Arabic among them no less than Greek and Latin.

Mathematics

As with astronomy, Muslim thinkers interested in mathematics had several traditions to draw upon. One of these was the existing system or systems of calculation and estimation used by merchants, traders, builders, surveyors, and so on. This undoubtedly helped prepare some people for more advanced, written mathematics when it arrived. Here, we can speak once again of Greek and Hindu influences. Most of these, however, were quite advanced; thus, it is no surprise that they were very often first translated and absorbed by Persian thinkers. Still, it wasn't until the late 8th and early 9th centuries that this material began to be studied and employed.

Yet the mathematical bounty from these two scientific cultures was enormous. From India came the decimal system and the zero, as well as the use of sines and cosines, thus early trigonometry. Means of working with equations containing unknowns and methods of solid geometry were also part of this. Translation brought the geometry of Euclid, understanding of conic sections and more from Apollonius, plus the method of exhaustion and many geometric procedures and proofs of Archimedes. Another favored author was Diophantus of Alexandria (3rd c. C.E.), who wrote on methods to solve algebraic-type equations. Finally, there was the compendium of Greek mathematics, *Synagoge* ("Collection"), by Pappus of Alexandria (4th c. C.E.), which had little impact in its own time and had to wait for Muslim readers before its value was appreciated.

All of this material, plus the mathematics in astronomical works such as those from Ptolemy and Brahmagupta, took time to comprehend and synthesize. Simplified summaries proved very helpful for establishing a base of teaching material that then encouraged more advanced understanding and, eventually, innovation. It does not appear that Muslims were much impacted by Chinese mathematics at this time, though they may well have been later on, in the Song Dynasty era and after. Nonetheless, they had available to them the pinnacles of ancient mathematical thought from the Mediterranean to South Asia.

By the 11th century, Muslim mathematicians had made a number of major advances. Trigonometric functions were expanded to include tangent, cotangent, secant, and cosecant. Trigonometry applied to a sphere and its surface created an early version of non-Euclidian geometry. Decimals were employed to express fractions, making it easier to work with equations having fractional coefficients. General methods for solving cubic equations were developed, as was an early mathematical notation for algebra. Procedures for determining the area under a parabola were also conceived, approaching the concept of integration. Such are but a very few of the advances made.

The syntheses Muslim mathematicians generated were impressive by any standard. They combined the practical with the theoretical, proving able to further astronomy and its religious uses as well as establish new domains, like algebra. Most of all, by bringing together and advancing the most sophisticated mathematical methods, Muslim scientists laid the necessary groundwork for the modern era in mathematics.

Alchemy

Muslim scientists also brought to a new level the thinking about chemical processes. Here, too, they were most influenced by Greek authors, which also meant Egyptian and Mesopotamian ideas. Much of the knowledge in this realm came from Alexandria, with some also from Persia and Nestorian centers. Muslim scientists who pursued alchemy moved it into a laboratory-type setting and standardized a number of its key processes. This involved such methods as distillation, crystallization, sublimation (heating a solid so that it turns directly into vapor), fermentation, and calcination (thermal decomposition of a substance, below its melting point). It is from alchemical texts in Arabic that we have acquired such words as: alembic, amalgam, alcohol, borax, camphor, elixir, and realgar.

Those who worked in alchemy were often trained as physicians, as was sometimes the case in ancient Egypt and Greece. Physicians were in the business of creating, mixing, and purifying substances for medicine, so the connection is no surprise. But there was a deeper, philosophical link, related to prolonging life. As we recall, a fundamental idea behind alchemy was that certain processes in nature transform "lower" or "base" substances to "higher" and "noble" ones. Such processes had the power to cure disease, purify a person of all evil, and thus extend life, even to immortality. The original goal was not to spin gold from lead but to find the key to other, grander dreams – to eliminate all illness from the Earth and to live forever.

In Islam, these ideas were partly adopted and transformed but also rejected. The most influential of all Muslim alchemists, the Persian Jabbir ibn-Hayyan (721–815), known in the West as Gerber, had a goal to actually create life in the laboratory. On the other hand, the mystical branch of Islam known as Sufism was also engaged in alchemical work, with the aim of reaching higher levels of spirituality. These types of ambitions, along with transmuting "base" metals into silver or gold, and the obscure language of alchemy (used by Gerber), came to be spurned by a number of Islam's major scientists, such as al-Kindi and Ibn Sina. Having worked with metals and chemical processes, they did not at all accept that transmutation was possible: a metal's appearance might change, said Ibn Sina, but not its substance. This division between alchemy and the beginnings of a materialist chemistry is important, though it was partly lost when transferred to Europe later on.

Gerber and also the great physician and polymath al-Razi were Islam's most important alchemists. Gerber wrote many influential works, including *Kitab al-Kimiya* ("Book of Alchemy"), which was translated into Latin in the 12th century. He introduced a number of terms into chemical discourse, such as alkali, from the Arabic *al-qali* ("from ashes"), and discovered methods to produce colored glass and glazes by embedding certain metal oxides and applying heat. Gerber also came up with ways to produce acids, including the highly corrosive mixture of sulfuric and nitric acid known as Aqua Regia. In addition, historians have credited to him discussion of the need to repeat experiments in order to confirm all results. Gerber's achievement was transformed into legend; as many as 3,000 different works were eventually attributed to him, making his true contributions difficult to ascertain in any precise way.

Medicine

It has been sometimes said that medicine progressed more rapidly in Islam than almost any area of science. Muslim physicians did have certain advantages that astronomers and mathematicians did not. One of these was the presence of a well-organized medical care system – including hospitals, teaching centers, professional licensing, and specialization, all supported by ruling elites – in Sassanid Persia. When the city of Jundishapur was taken by Arab Muslims in 638, they encountered Nestorian and Persian physicians using techniques far more sophisticated and effective than their own. The city was home to a great academy with a vast library, and it had the most renown hospitals in all of Persia, which acted as teaching centers as well as care facilities.

These institutions, therefore, were left intact and taken as models. Up through the 10th and 11th centuries, hospitals were non-religious, non-sectarian institutions. Their doctors could be Christians, Zoroastrians, Muslims, or from other backgrounds. Arab medicine had relied on herbal therapies, so there was no conflict with similar therapies in Persian, Greek, and Hindu practice. Indeed, under Islam, with its enriched and populous cities, pharmacy developed into a separate profession, with state-inspected shops and hospital dispensaries selling medicines, ointments, salves, and so on. A significant trade in medicinal substances existed, perhaps with some involvement of China.

Persian medicine had itself been influenced by Hippocrates and Galen. The theory of the four humors – blood, phlegm, black bile, and yellow bile – was central and acted to sway the Arab patrons of translation toward Greek authors. The works of Galen were especially favored for another reason as well: his insistence that the human body was created by one god. Next in importance was the Hippocratic corpus, though it tended to lose influence with time to Galen and to a third author. This was Dioscorides (1st c. C.E.), whose single work, *De Materia Medica* (as it is known in Latin, meaning "On the Substances of Medicine"), with its detailed discussion of herbal medicines and poisons and its illustrations of individual plants, proved hugely influential in Islam and Europe, to the point of serving as the primary model for future herbals in the Renaissance.

Two central ideas in Galenic and Hindu medicine (also in Chinese medicine as well) adopted by Muslim physicians were the need for close clinical observation and for therapies able to restore balance in the individual person. Detailed inspection of a patient's symptoms was essential to any diagnosis; different diseases or illnesses could display similar signs at a superficial level. As for balance and bodily harmony, these could often be achieved using the methods of nature – healthy food, strengthening exercises, avoidance of damp and dark environments, comfortable surroundings.

Muslim scientists: a selection

What follows is a small selection of Muslim thinkers who contributed at the highest level to scientific thought in early Islam and who had a powerful impact in Europe. It is not a wholly representative selection nor could it be. Any list of influential authors would run into many dozens. A smaller number, however, would appear at the top of any such list, and it is from this group that the following six authors are chosen.

What often strikes the modern reader about the scientific culture that evolved in medieval Islam is how widely its thinkers roamed across the domains of the physical and life sciences, as well as philosophy, ethics, theology, and more. The "polymath phenomenon" becomes less surprising when we think about the lack of any established boundaries among these areas and that the example of Aristotle stood out. Muslim polymaths thus reveal, overall, an exploratory intellectualism of the highest order.

Al-Khwarizmi

Mohammed ibn Musa al-Khwarizmi (780–850) was a Persian astronomer and mathematician from the district of Khwarism (Uzbekistan area of Central Asia). He apparently had come to the early notice of al-Mamun, and once the latter became caliph, was requested to join him in Baghdad as part of the *bayt-al-hikma*. Al-Khwarizmi was not a translator, though he knew both Persian and Arabic. Instead, he was employed as a mathematician and astronomer and as an author of more popular works on topics al-Mamun believed would be important to the educated public.

Al-Khwarizmi's fame and influence are due to three epochal works. These had an enormous impact in Islam and, later, in Europe. Historically, they combine Persian, Hindu, and Greek elements and represent a turning point, when Muslim scholars began to compose original works. The impact of these works was partly due to their being written for a large audience, as well as for professional astronomers and mathematicians.

The first work helped introduce the Hindu numerals and decimal system to Islam. It has no title, and no version exists in the original Arabic, only in untitled Latin translations. It is today known as *The Book of Addition and Subtraction According to Hindu Calculation,* a label from the 19th century. Since he did not know Sanskrit, al-Khwarizmi must have based his own Arabic text on Persian works that used the Hindu system. Muslim mathematicians never fully accepted the new system, though merchants came to do so. Mathematicians continued to rely mainly on a version of the sexagesimal (base-60) system developed by the Babylonians. Al-Khwarizmi's treatise and a book on Hindu mathematics by his contemporary al-Kindi had more impact in Europe, where the Hindu system came to be known as "Arabic numerals."

A second work of importance, written around 820, was also based on Hindu usage. This was the famous *Zij al-Sindhind*, or "Astronomical Tables Based on Hindu Methods," requested by al-Mamun, that made more accessible the material in a translation of Brahmagupta's famous *Brahmsphuta-siddhanta*. This work had been translated into Arabic a half-century earlier, on the order of Harun al-Rashid. The term *Sindhind* in al-Khwarizmi's title refers to the *siddhanta* ("compendium") genre of astronomical writings in India. Al-Khwarizmi was not the first to compose a *zij*, but his version turned out to be more useful because it took account of religious needs. It contained as many as 116 tables on the movements of the Sun, Moon, and planets; star positions; computations of eclipses; and also first appearances of the crescent Moon; calculations for the Islamic calendar; and geographic latitudes and longitudes (helpful for *qibla*).

Al-Khwarizmi's greatest fame, however, comes from his enormously important book on algebra, *Al Kitab al-Mukhtasar fi Hisab al-jabr-w'al-Muqabala*, "Compendium on Calculation by Restoration and Balancing". Composed about 830, the book draws together existing methods and some new procedures for solving equations up to the second power using transposition of terms. The word "algebra" comes directly from the *al-jabr* ("restoration") in the title. As this book is considered to be one of the most important in the global history of mathematics, it deserves a measure of attention.

In his preface, al-Khwarizmi states that al-Mamun requested the book and asked that it cover "what is easiest and most useful . . . such as men constantly require in cases of inheritance, legacies, partition, law-suits, and trade, and in all their dealings with one another, or where the measuring of lands, the digging of canals, geometrical computation," are performed. Though written as a manual for instruction, the book treated methods for solving linear and quadratic equations in a generalized way. Its first part offers definitions and simple examples to demonstrate the kinds of procedures used, i.e. adding the same quantity to both sides, dividing both sides by a term that will bring all unknowns to one side, and so on.

Al-Khwarizmi does all this in prose, as no symbolic notation yet existed. Here is an example, using his words "root" (for the unknown variable, x), "square" (x^2), and "simple number" (any rational number): "A square is equal to five roots of the same; the root of the square is five." In modern notation, this would be: $x^2 = 5x$, which, when we divide through by x, gives $x = 5$. Such examples proceed in difficulty up to quadratics (e.g. $x^2 + 5x + 2 = 0$). The rule is to get x^2 alone on one side of the equation, then take the square root.

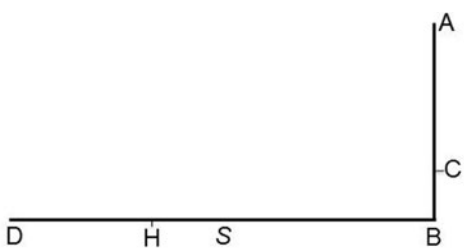
It is clear from the author's style that he is teaching. He moves from the simple to the more complex and does so in step-wise fashion, each new example building upon the last. A good instance of this is where he tells the reader how to use the distributive property for multiplying bracketed terms, e.g. $(10 + x)$.

He poses the problem this way: "ten and one, to be multiplied by ten and two," i.e. $(10 + 1) \times (10 + 2)$. This is to be solved just as we would do today: "Ten times ten is a hundred; once ten is ten positive; twice ten is twenty positive, and once two is two positive; this altogether makes a hundred and thirty-two."

Next, he does the same with minus signs inside the brackets ($(10 - 1) \times (10 - 2)$), then with one plus and one minus. Then he introduces an unknown variable: "ten and thing [x] to be multiplied by ten," in other words $(10 + x) \times 10$, "so the product is a hundred plus ten things," $100 + 10x$. From here, al-Khwarizmi proceeds to using two bracket terms with x. After this, he introduces fractions, e.g. $(10 + \frac{1}{2}x) \times (\frac{1}{2} - 5x)$. By now, the reader is comfortable with the process of multiplying out the terms.

Before moving on to practical problems, the author discusses how to perform an operation adding and subtracting terms that contain square roots. An example: "Know that the root of two hundred minus ten, added to twenty minus the root of two hundred, is just ten." In modern notation, this is: $(\sqrt{200} - 10) + (20 - \sqrt{200}) = 10$. We see that the two $\sqrt{200}$s cancel each other, while the -10 added to 20 gives us the final answer. This seems simple enough, requiring little explanation. But in al-Khwarizmi's day, there was no clear concept of the associative property, so a reader might confuse how to assign positive or negative values to each quantity. Understanding this, yet still wanting to provide an actual demonstration of why the answer is indeed 10, the author employs an ingenious explanation using geometry, as shown in Figure 7.5.

Al-Khwarizmi defines six fundamental problem types, each representing a type of equation that could be applied in real world situations. We recognize these as "word problems" today when such an application is done. But here is the first time in history such problems were posed as such. Taking the First Problem type as our example, we find it given in a generalized way: "I have divided ten into two portions [these can be written as x and $10 - x$]; I have multiplied one of the two portions by the other [$x(10 - x)$]; after this I have multiplied the [other] by itself [x^2], and the product of this multiplication by itself is four times as much as that of one of the portions by the other" [$x^2 = 4x(10 - x)$]. So we have our final equation, in modern notation. Al-Khwarizmi's instructions are just as clear: "Computation: suppose one of the portions to be thing [i.e. x] and the other ten minus thing: you multiply thing by ten minus thing; . . . Then multiply it by four . . . This is



Definitions

AB = √200	BD = 20 (i.e. 2AB)
AC = 10, therefore	BH = AB = √200
CB = √200 - 10	HD = 20 - √200

Problem asks for: CB + HD

Solution: Define length H*S* equal to CB. We know that AB = BH (see above), and thus AC = BS. So we know that CB + HD (the problem) is equal to SD. How long is SD? This is easy: BS = AC = 10; and since BD = 20, that means SD = 10, our answer.

Figure 7.5 Al-Kwarizmi's geometric explanation of the equation: $20 - \sqrt{200} + (\sqrt{200} - 10) = 10$.

forty things minus four squares [$40x - 4x^2$, representing the right hand side of our equation]. After this, you multiply thing by thing . . . This is a square [x^2], which is equal to forty things minus four squares [$x^2 = 40x - 4x^2$]. Reduce it now by the four squares and add them to the one square. Then the equation is: forty things are equal to five squares [i.e. add $4x^2$ to both sides to get $5x^2 = 40x$] and one square will be equal to eight roots [we can simplify this to $x^2 = 8x$], that is . . . the root of this is eight, and this is one of the two portions." That is, $x^2 = 8x$ reduces to $x = 8$; and our second unknown, $(10 - x)$, is 2.

Note that al-Khwarizmi does not say to divide both sides of the last equation by "thing" (x). Nor did he tell us to multiply both sides of $5x^2 = 40x$ by 1/5 to reduce it to $x^2 = 8x$. The reader is expected to do this in his head or perhaps to realize it intuitively. Either way, there are missing steps in the explanation, though only a few. We are one step across the threshold of a new domain of mathematics but not wholly there. Major advances in science and mathematics almost never arrive complete.

Yet it is obvious that al-Khwarizmi's book is strikingly different from what we have seen up to this point. Rather than fixed rules for solving specific problems, we see universal procedures and reasoning. In this sense, al-Khwarizmi certainly represents a major advance over his predecessors. This, in fact, was recognized in Europe. Ideas from his book were included in the great work *Liber abbaci* (1202) by Leonardo of Pisa (Fibonacci), which set European mathematics on a new course.

Al-Khwarizmi, in fact, has never left the scene. His name is one that we speak daily from the "golden age" of Islamic science. Medieval Latin culture in Europe adopted him as the great Algorismus, which, over time and varied use, became algorithm. The irony here, of course, is that his book on algebra teaches us to go well beyond algorithmic rules.

Al-Kindi

Abu Yusuf Ya'qub ibn Ishaq Al-Kindi (800–870) represents a very different kind of intellect than his partial contemporary al-Khwarizmi. The first of the great polymaths that emerged in Islam between the 9th and 13th centuries, he studied and wrote about many subjects, but he was first and last a philosopher of rational thought and explanation, in the vein of Aristotle.

Born in Basra, the capital of Mutazilism, he was a member of the powerful Kinda tribe, a major supporter of Islam in its earliest years. Historians believe he received his education in Baghdad, where he was noticed by al-Mamun, due to his precocious command of Greek philosophy, and employed at the *bayt-al-hikma*. He also had work as a physician and, under al-Mamun's successor, al-Mutasim, was appointed tutor to the caliph's son. At the *bayt-al-hikma*, he was placed in charge of one group of translators and assistants, with Hunayn ibn Ishaq overseeing another. Al-Kindi's circle was responsible for rendering scientific and, especially, philosophical works by Aristotle, Plotinus, the neoplatonic Christian thinker John Philoponus, and Proclus, among others. Many of these works influenced him but none more deeply than the books by Aristotle.

Al-Kindi was not himself a translator, though he edited and polished the translations of others. He acted more as a wide-ranging interpreter of Greek and Hindu thought. He was a special kind of intermediary who absorbed an immense body of knowledge and made it available to Arabic speakers. He did this by writing many summaries, commentaries, and original explanatory works. His combined effort created for the first time a vocabulary in Arabic for discussing philosophical subjects, which he viewed as essential for any understanding of the world and the power of the divine.

Al-Kindi is rightly famous for his attempt to reconcile Islamic theology and Aristotelian philosophy. This might be called his primary aim (and hope). He was a devout Muslim, and part of his achievement was to establish the basic terms of debate regarding acceptance of Greek thought by orthodox Islam. During his lifetime, the debate was decided in his favor, in part due to his own influence. But this did not last. As noted already, Greek thought came under attack by conservative traditionalists during the reign of al-Mutawakkil (r. 847–861). Thereafter, as the empire broke apart into a shatter of smaller states, support from the upper levels of society became more localized and sporadic, and the concept that Greek, as well as Hindu, Jewish, and Christian, thought constituted a "foreign science" became hardened.

The range of al-Kindi's writings is apparent from his books that are known. One early work, *On the Use of the Indian Numerals*, helped make the Hindu system of numerals more widely known, just as al-Khwarizmi's text did. A text that he wrote in the form of a long letter, *On the Demonstration of the Finitude of the Universe*, argues against the Greek concept of an eternal cosmos and in favor of its creation and, therefore, a beginning for time – ideas that are in accord with the Qur'an. Another work, *The Deceits of the Alchemists*, provided an assertive argument against alchemy, based on Aristotle's concept of original substances, which cannot be altered into each other. In *Burning Mirrors*, the author takes up the subject of optics, in part as treated by Euclid. Here, he accepts the basic theory of Greek authors that light is produced by the eye, which emits rays and makes objects perceptible. This idea would remain intact for another two centuries, until overturned by al-Haytham.

Of all his writings, it is *The First Philosophy* for which al-Kindi is best known. This is about the nature of the world, the importance of knowledge, the role (and weakness) of our senses, the place of mathematics, and more. Though written in the mode of Aristotle, as a series of logical arguments leading to conclusions, it is not purely Aristotelian. Instead, the author merges philosophy, science, and theology. He begins by stating that the highest and most noble "art" is philosophy, defined as "knowledge of the true nature of things." He says "the cause of the existence and continuance of everything is the True One. . . . Thus the pursuit of truth, even about material things, leads us to God, origin of all." As for science, al-Kindi has this to say:

> Scientific inquiries are four . . . either "whether," "what," "which," or "why." "Whether" is an investigation only of the existence (of something); "what"

> investigates the genus of every existing [thing]; "which" investigates its specific difference; "what" and "which" together investigate its species; and "why" its final cause. . . . When, therefore, we obtain full knowledge of its matter, form, and final cause, we obtain full knowledge of its definition. . . .

Muslim thinkers, it turns out, often wrote about the process of deriving knowledge regarding nature. Al-Kindi here approaches a definition of reductionism – the analysis of a phenomenon by breaking it down into a series of simpler components that can be individually studied and described. Al-Kindi's descriptions of these components, e.g. "investigation only of the existence [of a phenomenon]," can be easily, if not perfectly, translated into more modern terms: "study of the natural setting and occurrence [of the phenomenon]." His use of the interrogatives works as a concise introduction to what science tries to do and also suggests that it has no conflict with the "nobler" understanding of the divine.

This leads us to consider a final passage, which is often quoted to show al-Kindi's position toward *falsafa*:

> We must not be ashamed to admire the truth or to acquire it, from wherever it comes. Even if it should come from far-flung nations and foreign peoples, there is for the student . . . nothing more important than the truth, nor is the truth demeaned or diminished by the one who states or conveys it . . . rather, all are ennobled by it.

It would be difficult to find a more articulate statement of the ideals that scientists have tried to realize.

Can science teach us how to behave?

Do the sciences offer a guide for living? Can they teach us ethics? These have long been debated questions. One view is that facts and values exist in separate realms: to know the boiling point of lead will not help us decide if lying is ever justified. Another view holds there are virtues science can teach: teamwork, patience, respect for truth.

Muslim thinkers took up these matters with much seriousness. Many of them wrote on how knowledge and reason might play in a moral life. But the most interesting answer to our question comes from al-Kindi, in a brief text, *On the Means for Dispelling Sorrows*.

Al-Kindi makes use of Stoic thought, especially Epictetus (c. 55–135 C.E.). This philosophy says we are burdened by attachments in this life, material and emotional, and should learn to give them up. Like Epictetus, al-Kindi suggests we are better people if we avoid sorrow, anger, and other passions. Sorrow is due to "the loss of something loved or the failure to obtain something desired." We suffer "because in the world of generation and corruption in which we find ourselves, nothing is permanent." Al-Kindi does not say, as Epictetus did, that we must view all love, even for family, as "encumbrances." Neither does he advise we be indifferent to all desire. He is not the stone Epictetus was. We can avoid sorrow, he says, by keeping to the things that make us happy. But there is also a "cure" that the Stoics never found:

> [I]f we want neither to lose the things we love nor to fail to obtain what we desire, we should look to the world of the intellect and make what we love, own, and desire [come] from it. If we do that, we will be safe from someone forcibly taking our possessions or some power lording them over us; we shall [be safe against] losing what we loved of them since neither does misfortune reach them nor does death cling to them.

Al-Kindi is not speaking of faith. He makes no mention of God or religion. That he has just spoken about "the world of generation and corruption," directly invoking Aristotle's famous work (*On Generation and Corruption*) makes plain his intent.

The realm of the intellect, with scientific knowledge at its core, can never be taken from us, once we have it. A higher, incorruptible possession, it has the power to be an ethical anchor, a guarantee against loss. Al-Kindi suggests that we consider science nothing less than a victory over death itself, thus something that can keep us from evil thoughts and harmful passions. Such is not how we tend to pose the debate over science and ethics today. Or is it? What of the idea, no longer rare, that understanding the brain and how it works will grant us the key to "human nature," thus how we might be made better beings?

Al-Razi

Mohammed ibn Zakariya al-Razi (865–925) is considered today the greatest physician of medieval Islam. Yet like other powerful minds of the period, he delved into many realms and wrote about most of them. In direct contrast to most other scholars of *falsafa*, al-Razi did not find Aristotle a valuable source but was a strong follower of Galen and Hippocrates. In Latin Europe, where he was known as Rhazes, it was his medical writings for which he was valued. Indeed, a large collection of these was printed as early as 1486, a mere three decades after invention of the printing press.

He was born in the Persian city of Rayy (Tehran), an important stop on the Silk Road. Most likely, he received an excellent education that included the new sciences from India and Greece. Different traditions say that he was either a musician before he studied medicine or an alchemist. Another view is that he knew Greek and worked as a translator. It is known for certain, however, that, while still a fairly young man, he was made chief physician of a major Rayy hospital and was soon after called by Caliph al-Muktafi to Baghdad to be the director of a new hospital there.

A famous story (unconfirmed) says that he determined the most sanitary location for the new building by hanging strips of meat in different parts of the city and observing where it took the longest time for rot to begin. When the caliph died in 907, al-Razi went back to Rayy to assume his former position. Yet his fame was such that when the new caliph, al-Muqtadir (r. 908–932), had a series of new hospitals erected, al-Razi was recruited to be director of the largest and most prominent among them. In the later part of his career, he turned to writing, teaching, and mentoring. He suffered from an eye condition, possibly glaucoma, as well as cataracts, and in his final years seems to have gone nearly blind.

He remains among Islam's most freethinking intellectuals of all time. A skeptic toward miracles, omens, and even prophecy, he spoke openly against the turn to traditionalism in religion and how it often denied the value of rational thought and analysis. His most well-known words on this subject are these: "If the people of this religion are asked about the proof for the soundness of their religion, they flare up, get angry, and spill the blood of whoever confronts them with this question. They forbid rational speculation, and strike to kill their adversaries. This is why truth became thoroughly silenced and concealed." Al-Razi went even further than this, calling the Qur'an itself "a work which recounts ancient myths." Yet he was never brought to account for such statements by the authorities, so great was his reputation. This remains the case today in Iran, where al-Razi retains an eminent reputation and is a source of national pride.

What was al-Razi's medical philosophy? He believed all true physicians should be philosophers, informing themselves and meditating throughout their lives on the most basic questions about life, its origin, purpose, and organic nature. One of his central principles was that all human beings, whether rich or poor, deserve the best medical care available. To help combat quackery, he wrote a short work on home remedies for ordinary citizens and the poor.

In his own clinical work, he seems to have been entirely true to his word, refusing to stop treatment of any person if a wealthy aristocrat called for his services. At the same time, he was both worldly and practical in this regard. Among his many works are some that deal with the relationship between doctor and patient. This must, he said, be based on trust and confidence for both sides – patient should feel that the physician is competent and will help him; the doctor, that the patient will follow his instructions and not blame him for the result if they are ignored. He notes in his writings that medicine given to the wealthy needs to be sweetened in some way; the suggestion is that this be done both to make the substance more palatable and to reflect a higher social status. Recipes for the poor do not require such coddling additions.

Like al-Kindi, he was a vigorous proponent for seeking what the past had to offer. "He who studies the works of the ancients," he wrote, "gains the experience of their labor as if he himself had lived thousands of years spent on investigation." But this did not mean accepting everything at face value. Therapies needed to be tested, evaluated, criticized if need be, and improved. Though an ardent follower of Galen in many areas, al-Razi wrote a work titled *Doubts on Galen*, where he corrects some of the Greek's errors.

Clinical experience, therefore, was sometimes a better teacher than even the highest authority. True to his advice, al-Razi wrote the first known work describing in clear detail the different symptoms of smallpox and measles. An ancient disease, which saw epidemics in ancient Rome, Syria, India, and elsewhere, smallpox was likely responsible for a number of historical outbreaks of what was called "plague." Al-Razi's description would help settle the matter from then on: "a continued fever, pain in the back, itching in the nose, and terrors in sleep . . . then also a pricking which the patient feels all over his body . . . vehement redness in both cheeks; a redness of both the eyes . . . pain in the throat and chest, with slight difficulty in breathing and cough; a dryness of the breath . . . an inflamed colon, and shining redness, especially an intense redness of the gums." This treatise, *Kitab al-Judari was al-Hasbah* ("The Book on Smallpox and Measles"), had a potent impact in Europe.

Like Galen, al-Razi advises that one must always be open to the unexpected. He says this, for example, with regard to a single method of diagnosis regarding 2,000 patients, whose records he had examined.

> A careful intellectual ought not to desire in [any] method the utmost certainty, and ought not to rely on it and make absolute statements on prognoses or deduce the treatment and regimen in accordance with it. For there were approximately three hundred out of two thousand patients whose state developed in a contrary fashion. . . . For a time I continued seeking through experience and reason a new regimen for acute diseases . . . my only fault being my inability to find a speed cure.

This appreciation for the complexity and even messiness of illness in its real world occurrence is impressive, to say the least. The author is essentially telling his readers that nature is simply too complicated for the physician to be right all the time.

Though he wrote many works, more than 200 according to later Muslim scholars, the most influential of these was *Kitab al-Hawi fi al-tibb* ("Comprehensive Book of Medicine"). This was translated into Latin in the early 13th century as *Liber Continens* and underwent many printings in the 15th and 16th centuries. It is based on an extensive collection of notes, observations, clinical descriptions, summaries and criticisms of readings, and researches that the author made over decades of practice. Assembled into 23 volumes, each focused on a group of illnesses, *Kitab al-Hawi* is a monumental work that brought to Europe a wealth of new knowledge. Al-Razi advises doctors to gain experience practicing in large cities, where the widest range of diseases and conditions are seen. Not surprisingly, he also counsels that doctors keep an open mind about new methods of diagnosis, therapeutic techniques, medicines, and any other areas of advancing knowledge.

If all this makes al-Razi seem like a 21st century doctor sent back in time, we might consider a passage from *Kitab al-Hawi*: "I am of the opinion that bloodletting at the corners of the eye and the vein of the forehead is useful against all chronic eye diseases. . . ."

For epilepsy, he prescribes a medicine that provokes sneezing and claims to have cured a number of patients this way. And for melancholia (depression), as well as for many illnesses with physical pain, including arthritis, he adopts the use of opium (often applied externally, using a damp cloth), which had been in use since at least Babylonian times, but without noting its addictive aspects. Moreover, the actual grouping of diseases in *Kitab al-Hawi* was based more on symptoms than causes. The same volume that includes varicose veins also covers gout, piles, kyphosis (hunchbacks), abdominal worms, and elephantiasis.

Al-Razi was no modern in medieval garb. But he is a sure sign that medicine had advanced beyond classical times in key areas. Though he accepted ideas from Galen above all, he is an early proponent that therapies be tested and re-proven; that patients also be observed in groups to determine the effectiveness of therapy; that physical and mental illnesses be considered equally; that religion not be used as a basis for medicine; and that all human beings deserve medical care, irrespective of their social and financial condition. In all these concepts, al-Razi was indeed a forerunner of the future rather than a follower of the past.

Ibn al-Haytham

Abu Ali al-Hassan ibn al-Haytham (965–1039), known as Alhazen to late medieval and Renaissance Europe, was a brilliant thinker in many areas, above all physics, astronomy, and mathematics. His work on optics, in particular, overturned 1,300 years of misinterpretation, starting with Euclid and continuing down to al-Kindi and his own time. The influence of this work was profound, most of all in Europe, where it impacted thinkers from Roger Bacon (13th c.) to Johannes Kepler and beyond. Nonetheless, a number of al-Haytham's manuscripts have not been translated from Arabic into other languages and have yet to be fully studied and discussed by scholars.

Born in Basra, then part of the Buyid Emirate, al-Haytham was from a fairly well-to-do Arab family that could afford an excellent education for their son. There is mention in his autobiography that he studied theology and trained for work as a government official and, while still a young man, was appointed minister for Basra and environs. This did not suit him very well, however, and he left or was dismissed from the position. He continued to study religious thought in different sects of Islam, as well as Christianity and Judaism, and had concluded that none of them could adequately explain the world. Turning to *falsafa*, he found the works of Aristotle more to his liking and proceeded from there to many texts of Greek and Hindu science. The title for one of his early writings shows this shift: "All Matters Secular and Religious Are the Fruits of the Philosophical Sciences."

According to sources, al-Haytham personally wrote 90–100 different works. As many as 55 of these have been identified, though many are not yet available in scholarly editions. A large majority concern mathematical astronomical subjects. Some, such as *Model of the Motions of Each of the Seven Planets*, are only partly preserved, with less than half the original text. Works that he wrote on logic, politics, poetry, music, ethics, and theology seem to have been lost. Though known as an astronomer and mathematician in Islam, Europe mainly appreciated his writing on optics, which was translated into Latin, Hebrew, and Italian. This last language is particularly significant, since al-Haytham had a distinct influence on Renaissance theorists of perspective, such as Leon Battista Alberti.

In his mathematical works, al-Haytham showed himself interested especially in geometry, in which he truly excelled. He was intrigued, for example, by three-dimensional forms, deriving methods for calculating the volume of solids like the sphere and paraboloid. He also proved that among solid forms having the same surface area, those with more sides have a larger volume, with the sphere possessing the greatest volume possible. Conic sections were another area of interest and originality for al-Haytham. He showed, for example, how geometric figures could be constructed using the intersections of conic curves. He also tried to reconstruct the lost eighth chapter of Apollonius of Perga's *Conics*. He used conic sections to solve what became known as "Alhazen's Problem": given two points opposite a reflecting surface, how to find the point on that surface where light from one of the two points reflects to the other.

But, as noted, his most sophisticated and influential work was the *Kitab al-Manazir* ("Book on Optics," c. 1025), known in Latin as *De aspectibus*. It is a work that combines a theory of vision with a theory of light, an anatomical discussion of the eye (to help explain how vision works), and experimental and mathematical investigations of reflection and refraction. As such, *Kitab al-Manazir* is a scientific work of the first order and has been placed by modern physicists and historians of science at the same level as the optical writings of Kepler and Newton. The work includes seven books, the first three of which are about light, vision, and perception, with Books IV-VI offering experimental evidence on reflection, and Book VII taking up refraction. Very clearly, al-Haytham intended to supersede the two most famous texts on the subject, Euclid's *Optics* and Ptolemy's *Optics*. This meant persuading readers to abandon the past with all its weight of authority. How did the author achieve this?

While full discussion of al-Haytham's treatise is well beyond our scope here, we can answer this essential question with some selective comments. Book I of *Kitab al-Manazir* (*De aspectibus*) begins with an arresting image: "when our sight fixes upon very strong light sources, it will suffer intense pain and impairment . . . for when an observer looks at the body of the Sun, he cannot do so properly because his vision will suffer from its light." What child has not done this, stared at the Sun and endured a moment of pain and blindness? Al-Haytham, that is, makes us call upon an "experiment" we have all performed at some point and then extends it by also posing the case where we look directly "at a polished mirror flooded with sunlight." From the very start, therefore, the author helps us realize from our own experience that light comes to our eyes from external sources, thereby disproving in the simplest but most convincing manner that the traditional idea of the eye as producer of illumination is false.

What comes next is a series of chapters based on empirical observations about light, vision, and color. Many of these observations come from simple experiments:

> And we also find that when an observer looks at a thickly planted garden illuminated by sunlight and continues to stare at it, then shifts his focus to a dark location, he will see the form of that light tinged by the green of those plants. . . . Afterward, under the same circumstances, if he stares at white objects lying in shadow or in a weakly illuminated location, he will see those colors mixed with green. . . . These instances therefore indicate that illuminated colors may affect vision.

The author is among the first to point out this phenomenon of after-image. A large part of Books I–III contain little narratives of this kind. Al-Haytham is himself the "observer," of course, and the accumulation of evidence not only confirms beyond all doubt the eye as a receiving apparatus, plus many corollaries, but also that the interaction between light and vision is complex and multifaceted. He discusses the visibility of stars at different times of day, incandescence in marine animals, the light of fireflies, and other phenomena. He argues, again through small, systematically ordered experiments, that color is not the same as light but a property of objects: "solid bodies that are tinged with such bright colors as azure, wind-red, or sky-blue appear of a dull color when they are in dark or dimly lit locations" and "when strong light shines upon bodies whose colors are dull, their colors brighten."

It is crucial to understand the significance of what al-Haytham is doing. His careful, exhaustive use of detailed evidence, to the point of redundancy, compels us to accept his conclusion: "the form of the visible object that sight perceives depends entirely upon the light possessed by that visible object, as well as upon the light that shines upon the eyes when that visible object is perceived, and upon [the light that illuminates] the aerial medium between the eyes and the visible object."

This way of proceeding can be seen as a precursor for how scientific writing would come to be shaped in Europe by the 17th century: presentation of evidence first, along with methods in how it was gathered, followed by an explanatory conclusion, or hypothesis, then confirmed by further facts. This fundamental approach, as a way of actually *doing* science, progressing from facts to generalizations to physical laws, using the process of induction, was set out by Francis Bacon in his book *Novum Organum* (1620). Islamic scientists, however, as shown by al-Razi and al-Haytham, were the ones to introduce the collection of "data" as an essential, primary element in this.

Such was a vital advance in the concept of scientific work and its goals. Is it possible that Bacon himself was influenced by this? Most certainly. There was widespread familiarity with Islamic scientific writings among European thinkers up through the 17th century. Yet in many cases hard evidence of such influence is lacking; the competitive nature of authorship and the importance of appearing original led scientific authors to be very selective in admitting their intellectual debts.

There are two other key contributions in *Kitab al-Manazir*. One of these was al-Haytham's correct explanation of the "Moon illusion," our experience of the Moon appearing much larger when near the horizon than when high in the upper sky. Ptolemy tried to explain this in the *Almagest* as a result of refraction, using another common perception. He said, "this is caused not by [its] shorter distance, but by the moist atmosphere surrounding the Earth, which intervenes between [the Moon] and our sight [and] is just like the apparent enlargement of objects in water." Refraction of light by atmospheric water is how this might be phrased today. Al-Haytham rejected this altogether. The size of a distant object, he said, can be accurately (though still imprecisely) judged only in relation to other intervening objects: "sight perceives the difference between two different forms by a comparison of one to the other." These intervening objects exist for us only in the lower parts of the sky, while at more elevated angles from the horizon, the sky resembles a single, vast plane or wall without any visual reference points. In modern terms, the Moon illusion is a psychological phenomenon.

The other contribution that deserves our notice is al-Haytham's use of controlled, laboratory-styled experiment, discussed in Books IV and V of *Kitab al-Manazir*. His use of experimentation, in fact, represents a continuation of earlier efforts by al-Kindi and others, then expanded by those working on "burning instruments" (mirrors and lenses able to focus sunlight to a point). Al-Haytham made use of the work of his partial contemporary Ibn Sahl (940–1000), who did controlled experiments with curved lenses and mirrors, measuring how they bent and focused light, deriving an approximation to the law of refraction (Snell's Law). Al-Haytham repeated and modified a number of Ibn Sahl's experiments, as well as performing many of his own. He struggled with a mathematical explanation for rainbows, based on light behavior with concave mirrors, but could not fully complete it. Instead, one of his later admirers, and an excellent scientist in his own right, al-Din al-Farisi (1267–1319) was able to do so via a most elegant and ingenious experiment employing a spherical glass vessel filled with water, as a modeled raindrop.

A number of al-Haytham's experiments made use of a camera obscura (also "pinhole camera") – literally "dark room," meaning a darkened chamber or box with a small hole in one side through which light passes and casts an upside down image on the opposite wall or side – a device known since antiquity but never adequately explained. Al-Haytham accurately accounted for why an image is cast and why the smaller the hole, the clearer the image.

Such are among the reasons why al-Haytham is considered today among the greatest physicists of the pre-modern era. What impresses us, perhaps, given that he wrote a thousand years ago, is his awareness of what he was doing and how he had gone about it. As he says in the preface to the *Kitab al-Manazir*, the process of science

> should distinguish the properties of particulars, and gather by induction what pertains to the eye when vision occurs and what is found in the manner of sensation to be uniform, unchanging, manifest and not subject to doubt – After

> which, we should ascend in our inquiry and reasonings, gradually and orderly, criticizing premises and exercising caution in regard to conclusions – our aim in all that we make subject to inspection and review being to . . . seek the truth and not to be swayed by opinion.

Ibn Sina

A contemporary of al-Haytham in the more easterly parts of Islam was Abu Ali al-Husayn ibn Sina (980–1037), later known by his Latin name, Avicenna. A Persian polymath who produced enormously influential works on philosophy and medicine, he was known both as "the first teacher" and the "Prince of Physicians." He was born in the town of Afshana, close to Bukhara (present-day Uzbekistan) which had long been a major stop on the Silk Road. A gifted prodigy, he is said to have mastered the Qur'an and Arabic grammar by the age of 10 and proceeded, under several eminent teachers, to absorb a good deal of *falsafa*, including science and medicine, during his teens, as well as Islamic law. It is said that at 17, he was able to cure Nuh ibn Mansur, ruler of Burkhara, of an unidentified illness and thereby, instead of monetary reward, was given full access to ibn Mansur's extensive library.

Ibn Sina found himself caught up in the shifting wars and political turmoil that brought havoc to Central Asia and Persia. He was impelled to leave Bukhara when the city was invaded in 999, traveling southeast to Jurgan in Khwarizm, where he met and befriended another famous scholar of the first order, al-Biruni. His stay in Jurgan, however, did not last long. For reasons of safety and opportunity, he subsequently moved to Rayy, then Hamadan, then Isphahan, where he had residence for some years and was able to compose many of his works, but eventually returned to Hamadan, where he died. The stresses incurred during these frequent moves, as well as the long hours spent studying and writing, took their toll and may have contributed toward an early death. Nonetheless, he is also reputed to have been rather arrogant, always ready to correct others with whom he might debate. He presumably said: "Medicine is not a difficult science, and in a short space of time, of course, I excelled in it, so that the masters of physic came to read with me. . . . If a problem was too difficult for me, I repaired to the Mosque and prayed, invoking the Creator of all things until the gate that had been closed to me was opened."

Be that as it may, Ibn Sina wrote a great deal. Estimates vary on his total output – biographers and commentators make mention of up to 276 writings, including brief treatises and long letters. He wrote nearly all his books in Arabic, more than ever the language of scholarship though the empire had become splintered into a half-dozen emirates. He was an unparalleled synthesizer of ideas from *falsafa*, from predecessors like al-Kindi and al-Farabi, and from Islamic theology as well. He wrote many shorter treatises on specific problems, e.g. an argument against alchemy, a discussion of the pulse, the nature of minerals. He also wrote on religious questions, like the soul and free will, and produced commentaries on the Qur'an. He was the leading force in his time for compatibility between Islam and *falsafa*.

His major writings took the form of enormous compendia. One of these, *Kitab al-Shifa*, or "Book of Healing," many hundreds of pages in length, included four large segments on logic, metaphysics, natural science, and mathematics. The work was so vast in scale, that the author himself wrote a summary of it (*Kitab al-nijat*, or "Book of Deliverance"). His second massive volume, *Qanun al-Tibb*, the renowned "Canon of Medicine," became the standard reference for medical learning both in Islam and Europe for more than half a millennium, possibly equal to Galen in fame and use.

The *Kitab al-Shifa* was Ibn Sina's single-volume "corpus" that took as its model the combined writings of Aristotle. Known in Latin as the *Sufficientia*, the book sometimes follows the organization of earlier works, including Aristotle's, and paraphrases their contents. But it nearly always includes commentary and Ibn Sina's own ideas and conclusions. Only about half of the total work was translated into Latin, including the sections, in modern terms, that range from astronomy and chemistry to psychology and paleontology. Many of these sections were translated as separate works and sometimes combined with the writings of other authors on the same topics. More than a few of these had profound impacts on European scientific thought. An example of this is Ibn Sina's explanation for how fossils are formed: "the cause of this is a powerful mineralizing and petrifying virtue (liquid), which arises in certain stony spots, or emanates suddenly from the earth during earthquakes and subsidences, and petrifies whatever comes into contact with it." This idea, that fossils represent the mineralized remains of once-living plants and animals, became the generally accepted view in Europe by the end of the 16th century.

When we turn to *Qanun al-Tibb* ("Canon of Medicine"), we find that it, too, is a kind of summation mainly of Greek and Islamic sources, with information taken from translated Hindu sources as well. Modern scholars have also claimed that Ibn Sina drew on Arabic translations of Chinese medical texts, which might well be expected. Ibn Sina wrote it, apparently, because he felt there were too many competing, redundant treatises. A single, comprehensive work, well-organized, easy to study, to teach from, available in every library and hospital, would itself mark a considerable advance.

In all of these aims, the author proved to be prescient. The result, however, contains over a million words. It is divided into five main segments: the nature and general principles of medicine (Book I); a list of specific drugs and medicines (Book II); local diseases, their external and internal signs and symptoms (Book III); general diseases affecting most or all of the body, plus cosmetic treatment and repair (Book IV); and more complex, compound medicines (Book V). What seems to have been altogether new was the frequent use of full-page illustrations (Figure 7.6), providing a visual dimension that had been minor or altogether lacking before this.

Ibn Sina begins with a famous definition of medicine that will sound quite familiar:

> Medicine is the science by which we learn the various states of the human body, in health, when not in health, the means by which health is likely to

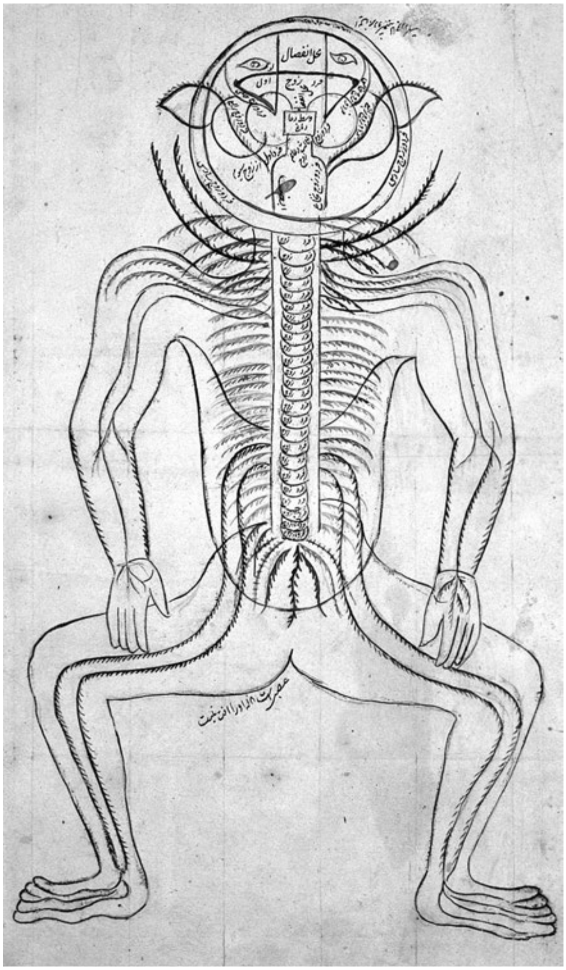


Figure 7.6 Diagram showing nerves of the human body, from the back, from the Persian work *Anatomy of the Human Body* (*Tashrih-I insan*) by Mansur ibn Ilyas, a follower of Ibn Sina. No such full-page illustrations exist from before the last decade of the 14th century, and it is believed this image was originally copied from Ibn Sina's *Qanun* (Canon). © Wellcome Library, London.

> be lost, and when lost is likely to be restored. . . . In other words, it is the art whereby health is conserved and the art whereby it is restored, after being lost.

Health is something we naturally possess, as living beings, not something we strive to achieve. This fundamental view, we now know, was shared by Chinese, Hindu, and ancient Greek thought, and before that, by the Egyptian, Mesopotamian, and Indus Valley civilizations. We might ask, therefore (as a subject for discussion), whether it differs from the modern view and, if so, in what ways.

Consider, as well, this statement from the *Qanun*: "there is no need to assert that 'there are three states of the human body – sickness, health, and a state which is neither . . . ' The first two cover everything."

Book I of the *Qanun* is especially central in terms of how health, illness, therapy, and medicines are conceived. Illness is discussed in terms of various divisions, such as "internal" and "external" and different causes: material (the organs, four humors); efficient (external environment, habits of life); formal (temperament, mental faculties); and final causes (actions and functions). The body's primary elements are those of Greek philosophy: earth, air, fire, and water, all integrated into the physical processes of the body. Each has two qualities, e.g. earth is dry and cold; air is hot and moist; water, cold and moist; fire, hot and dry. These interact with each other in a manner of dominance and passivity. Balance results from a dynamic equilibrium matched to the individual. The four humors, meanwhile, as the "vital essences" of the body, correspond with the four elements: blood with air; phlegm with water; yellow bile with fire; and black bile with earth. When the body is in a state of health, the humors are absorbed by the organs and tissues to the proper degree, with no surplus or deficit; illness comes from an abnormal state, when one or more humors cannot be assimilated and must be ejected from the body, whether by purges, laxatives, physical activity, bathing, or bloodletting.

Ibn Sina provides us with all of this information for a specific reason. For healing, it is necessary "that the causes of both health and disease should be determined." Physicians must have knowledge of science and how to put it to work: strict division between the theoretical and practical does not exist in medicine, since both are needed together whenever a diagnosis or therapy are performed.

For medicines, treated in Books II and V, the author has much advice. "You can tell the potency of drugs in two ways: by analogy and by experiment," with the latter leading to much greater certainty. By "experiment," however, he doesn't mean laboratory tests. Rather, he means using it on the patient and closely observing the results. Every time a drug is given, an opportunity for observation results. A drug can affect a disease directly, by lessening or curing it, yet may have secondary effects as well that treat only symptoms. In most cases, drugs should be chosen to impose an opposite effect to the illness, i.e. coolness if the condition involves a heated condition. The strength of a drug must match that of the illness and must be given adequate time to work. Its effects must be consistent for different patients, otherwise its results are "accidental" and not to be trusted.

The *Qanun* provides much advice about surgery. Consider, for example, a chapter on fractures of the skull. Ibn Sina says great care is needed for such a condition. This includes determining the story of what exactly happened, to the degree possible. Knowing why and how the injury occurred, what symptoms have resulted (mental confusion, nausea, aphasia), and what treatments have been given in the meantime are all essential elements to understanding the patient's status. The doctor must take care for other reasons as well:

> Sometimes the skull may be fractured, but the scalp may not be lacerated, just swollen. In such a case, if you attempt to treat [only] the swollen area . . . fractured bone may decay underneath. . . . [D]angerous implications may arise,

> e.g. fever, trembling, unconsciousness, etc. . . . [You should] tear open the scalp so that you can observe and cure the fracture. You can often detect the fractured area by the help of the patient. The patient puts his hand on the fractured area and points out the aching area. If you observe any indications of a fracture on the skull, leave the wound and swelling as they are, and start treating the fracture. Lift the scalp so that the purulent matter and [pus] do not accumulate in one place.

Ibn Sina's basic view of the human subject, as expressed in the *Qanun*, is similar enough to Christian ideas to have been easily adapted. Simply put, he saw a distinct division between the mind and the body, with illnesses specific to each domain. Christian Europe found such a division entirely compatible with its own notion of body and soul. No doubt, this aided the acceptance of Ibn Sina's medical book considerably.

Alongside the *Qanun*, and supporting it in some measure, was Ibn Sina's *Urjuzah fi al-Tibb* – the "Poem on Medicine." Using poetry as a way to teach readers about medicine and medical experiences was a literary tradition in Islam, reaching back centuries before Ibn Sina's time. As we've already noted, poetry defined a fundament for expression in the Arabic language, and the majority of authors on *falsafa* were also poets. Ibn Sina's *Poem on Medicine* became the most popular of all Arabic medical poems and was itself translated into Latin and widely used by students, possibly as a study aid to the *Canon*.

Al-Tusi

One of Islam's greatest mathematical astronomers, who not only critiqued Ptolemy's planetary model but produced an alternative to it, was the Persian thinker Nasir al-Din al-Tusi (1201–1274). Born in the city of Tus in northeastern Iran, he began his education by studying the Qur'an, hadith, Islamic law, and then progressed to *falsafa*, including philosophy, logic, mathematics, astronomy, and medicine. He first studied under his father and uncle, and then, showing great promise, went to nearby Nishapur, a bustling Silk Road city, to complete his education under eminent teachers.

Al-Tusi lived during the period when eastern Islam was invaded by the Mongols, who brought an end to the Abbasid caliphate and caused enormous damage to Muslim civilization. A famous (but exaggerated) story says that, in sacking Baghdad, Hulagu Khan emptied all the public and private library collections, throwing so many books into the Tigris River than a man on horseback could cross without getting wet.

The Mongol threat affected al-Tusi's life in major ways. While still a youth of 19, he left Nishapur when it became clear that Gengis Khan's troops were advancing on the area. He found sanctuary (some versions say he was forcefully taken there) in Alamut, the fortress capital in Khorasan of the Ismailite sect of Shi'a Islam. He apparently joined the sect and wrote a number of his important works while the city remained safe and intact. In 1256, however, it surrendered without a battle to the huge Mongol army under Hulagu Khan, grandson of Genghis. On the basis of his astronomical knowledge, al-Tusi was offered a position as astrological advisor to the Mongol court, which he accepted. He married a Mongol bride, gained a still higher position, and was able to persuade Hulagu Khan to fund a large new observatory in the city of Maragha (in present-day Azerbaijan).

In the following years, al-Tusi built a first-rate library and turned the observatory into a research center, inviting other important Muslim scholars as well as those from China to work there. For precise celestial observation, there was built a 4-meter (13-ft) wall quadrant made of copper. Using the observatory's apparatus, al-Tusi and associates produced the *Zij-i Ilkhani* (named for Ilkhan Hulagu, son of Hulagu Khan, who had died in 1265). This was produced for the observatory's Mongol patrons and may have well been hurriedly assembled under command. It is said to have some serious flaws, deriving some material from older *zij*s, not making adequate use of the Maragha observatory's own quality information. Nonetheless, it must be seen as an important historical document, for some of its astronomical information and for its description of the Chinese calendar system. Information on this was given to al-Tusi by one Fu Mengchi, who had come with the Mongols to Iran, perhaps as an astrologer. We might recall that the late 13th century was also the time when the Mongols in China appointed Muslims to positions as financial administrators, tax collectors, province governors, and, in Beijing, as official astronomers in an Islamic Astronomical Bureau.

Al-Tusi, meanwhile, like other great Islamic thinkers, wrote works on philosophy, ethics, logic, and Islamic theology, as well as the subjects for which he is best known, mathematics and astronomy. He also wrote on astrology and geomancy, showing that even the most advanced mathematical astronomers in Islam might either be believers in these occult disciplines or see the need to compose works about them. A unique aspect to his many publications (about 150 books, treatises, and letters are known) is that they include many recensions – reedited versions with commentaries – of earlier translations. This was an attempt to update the products of the translation movement and to create standardized editions for study and teaching. Just as Ibn Sina, whom al-Tusi greatly admired, had perceived a need for new sources to revitalize *falsafa*, so did the latter view his contribution in a historical light.

Thus, a chief role played by those such as al-Razi, Ibn Sina, and al-Tusi was that of textbook author. Such is a role we should never ignore or minimize. Why? Because many of the greatest works in the history of science were written as books to instruct readers about new knowledge, a fact as true of Aristotle as it was of al-Khwarizmi, al-Kindi, and al-Haytham. Al-Tusi's recensions focused especially on Greek mathematicians. This included translations of Archimedes, Aristarchus, Euclid, Apollonius, and Ptolemy. Interestingly, some 25 of al-Tusi's works are in Persian, with the rest in Arabic. His book on geomancy was even written in Persian, Arabic, and Turkish, for reasons that are unclear. Under the Mongols, Persian thinkers did return to using their own language more frequently than before, as a competing *lingua franca* to Arabic and a way to reassert their separate identity.

It is for his astronomical writings that al-Tusi is best known, particularly an elegant replacement for Ptolemy's model of planetary motion. This replacement was put forward in the author's book *al-Tathkira fi Ilm al-Hay'a* or "Memoir on Astronomy." Like Ptolemy's model, it is purely geometric, having no basis in any physical hypothesis about what causes the planets to move. But it is superior in that it is not only loyal to the ultimate idea of perfectly circular motion but is far simpler.

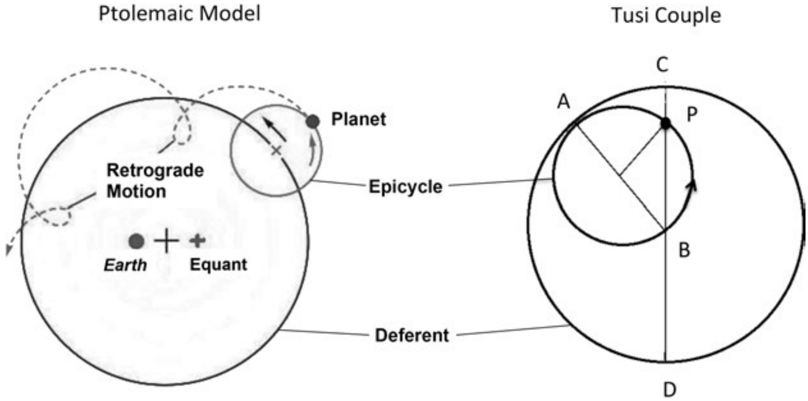


Figure 7.7 Comparison of Ptolemy's original model and the simplification introduced by al-Tusi using the Tusi Couple. See text for discussion.

A comparison between the two models is shown in Figure 7.7. As discussed in Chapter 4, the Ptolemaic model included an epicycle, off-center Earth, and an equant, with motion of the epicycle around the deferent occurring at constant angular speed. This produces the retrograde motion shown in Figure 7.7. Al-Tusi simplified the model considerably by drawing the epicycle as a small circle rolling at constant speed along the inner circumference of the deferent, twice its size and turning in the opposite direction at half its speed. This arrangement makes the planet (point *P* in Figure 7.7) move back and forth along a diameter of the larger circle (line CD), thus producing the retrograde motion, as seen from Earth. The historian of Islamic science, Edward S. Kennedy named this model the "Tusi Couple."

Copernicus and al-Tusi: A debt perhaps unpaid

The Scientific Revolution is routinely said to begin with Copernicus. And why not? After so many millennia, the Sun-centered view of the universe was finally established. But did Copernicus have help? George Saliba, historian of Islamic science, has written that his own research, as well as that of other eminent scholars, has determined that:

> the mathematical edifice of Copernican astronomy could not have been built . . . using the mathematical information available in such classical Greek works as Euclid's *Elements* and Ptolemy's *Almagest.* What was needed, and was in fact deployed by Copernicus (1473–1543) himself, was the addition of two new mathematical theorems. Both of those theorems were first produced some three centuries before Copernicus and were used by astronomers working in the Islamic world for the express purpose to reform Greek astronomy.

The Tusi Couple was one of these two theorems. Copernicus, in fact, employed it to solve the same basic problem, that of retrograde motion (Figure 7.8). He did not say this in his book *De Revolutionibus*. He cites several Islamic astronomers (al-Battani, al-Bitruji, Ibn Rushd) but not al-Tusi. The geometric innovation we see in the Tusi Couple had no tradition in Europe. It seems to have suddenly appeared with Copernicus.

The debt to al-Tusi seems revealed in another way. Copernicus, perhaps absent-mindedly or without noticing he was doing so, left traces of his borrowing behind. In a key figure illustrating how retrograde motion appears to someone on the Earth, he labels points in direct accord with a similar diagram in al-Tusi's text. Where the latter has the Arabic letter "Alef," Copernicus used the phonetically equivalent "A"; where the Arabic has "Ba," he used "B," and so on. A total of five out of eight letters occur this way, with the three extra having been added by Copernicus to his more complex figure.

Copernicus did not know Arabic. Al-Tusi's text was never translated into Latin. How might these two have met? Copernicus knew Greek and was in Rome at the time a Greek version of a Persian astronomical text, bearing al-Tusi's theorem, was known to exist. Also in Rome were Arabic versions of al-Tusi's text that had been annotated in Latin.

We may never know, for certain, the precise path of influence. In the meantime, should we consider Copernicus a possible intellectual pirate of sorts? This would be unfair. Incomplete mention of one's sources was routine practice in scholarship, both in Islam and Europe, and had been so for many centuries. The real question is different, and more important: might we see in Copernicus' scant attributions to Islamic authors a much wider denial of debt for reasons political and religious? Islamic authors, after all, were required reading in the universities of the 14th century but had largely disappeared 200 years later.

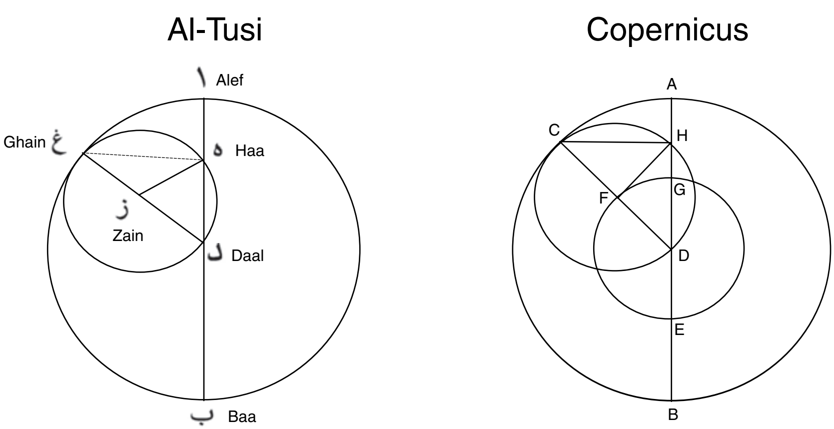


Figure 7.8 Comparison showing high degree of similarity between models of planetary motion by al-Tusi and Copernicus. Both thinkers proposed the same rolling motion that traces out a straight line (diameter of larger circle).

Concluding statement: the Islamic contribution

From what has been covered in this chapter, we should have no doubt whatsoever about the achievements of Islamic scientists. The old story of Islam as a container for the transport of Greek science to a long-awaited European homecoming can only seem like a fiction embarrassingly suited to an imperial age. Let us, therefore, put it to rest.

Having done so, we can take more accurate stock of Islam's contribution. Beyond the many discoveries and innovations it yielded, Islamic scientific culture introduced decisive elements for a more advanced science. One of these elements we have described already: the search for exact methods and the systematic production of new information. The likes of al-Razi and al-Haytham, for example, wrote treatises on the conditions needed to make detailed, accurate observations and described the kinds of errors that could result from poor quality instruments or improper use of them.

A second element was the questioning of authority. Call it the "critical spirit" or a "skeptical mind": the demand that previous work, no matter how famous its author, must be subject to review. As early as al-Kindi, Muslim thinkers found flaws in their Greek sources and set about correcting them. Al-Haytham wrote three separate books taking Ptolemy to task, two of which were rendered into Latin, one of which (*Doubts Concerning Ptolemy*) may have been known to Copernicus. Such skepticism was limited, to be sure. The geocentric universe, with uniform circular motion, was examined and accepted. Many Muslim astronomers were convinced of a stationary Earth by the simple thought experiment of throwing a stone in the air and finding it falls straight down, instead of being displaced westward. Yet others, like al-Tusi, denied that observation could decide the matter. It was never really settled.

So we come to the third key element introduced by Islamic scientific culture: the necessity of proof. Here, we return to the ambivalent attitude Islamic thinkers had towards Ptolemy, as an exemplar of elevated scientific thought yet, at the same time, a great reservoir of flaws and errors. These problems, Islamic thinkers felt, mostly came back to the use of "intuitive reasoning" and a reliance on mathematical constructions that seemed real only on paper. Al-Haytham was especially firm on this point: "Ptolemy assumed an arrangement that cannot be. . . . For a man to imagine a circle in the heavens, and to imagine the planet moving in it, does not bring about the planet's motion." Missing was actual proof, even multiple lines of analogy. And proof was essential.

These three elements, then – exact methods, use of skepticism, and necessity of proof – which Islamic scientific culture did not entirely invent but turned into institutions for the doing of science, had an impact on the future history of technical thought that would be hard to measure or exaggerate.

Yet this raises another matter. It may seem that a good deal is now known about Islam's "golden age," how and why it began, developed, and, eventually, came to an end. But the truth is that our understanding of this period is very incomplete. It turns out that only a small number of major works have yet been translated from Arabic into other languages and that there remain *thousands* of manuscripts yet to be studied. These texts are in libraries, museums, universities, and private collections across the Middle East and in other parts of the world. No individual, group, or institution has yet even assembled a bibliography of them. Therefore, what has been written about Islamic science can be considered akin to a rough draft. Much remains to be learned!

It is even possible that this vast literature will shed new light on the question of why Islam's "golden age" came to an end. Historians who have tackled the topic rightly point to a gradual decline not a sudden termination. They show that astronomy, due to its uses, was still patronized well into the 16th century. But for most of the rest of science, difficulties ensued. The Mongol invasions, as noted, destroyed the greater number of Islam's intellectual centers, including the great cities of Merv, Nishapur, Samarkand, Bukhara, Balkh, Herat, Rayy, Damascus, and Baghdad, all places where science had flourished. While the Mongols spared engineers, craftsmen, and astronomers (due to belief in astrology), scholars were usually killed or sent into slavery. Hulagu Khan intentionally leveled Baghdad in 1258, which, though no longer a political center, still had its priceless libraries. Many thousands of soldiers were set loose upon the city like wolves, to loot and murder at will, resulting in the deaths of between 200,000 and one million people. Though he later regretted such destruction and converted to Islam, Hulagu could hardly undo the damage done. Meanwhile, another wave of devastation came only a century later with the rise of Tamurlane. And starting in the 1100s, the retaking of Spain was launched, with the loss to Islam (and gain to Europe) of the great learning centers and libraries there.

There were religious responses. The failure of Muslims to withstand the "unbelievers" led to the idea that the faith had lost its way, with theologians calling for a return to the purity of Islam at its founding. Much attention has been given the powerful influence of the theologian Abu Hamid al-Ghazali (1058–1111), whose work *The Incoherence of the Philosophers*, written against Ibn Sina, was a major (though partial) attack on *falsafa* for leading believers astray. Some historians have noted the influence of other religious thinkers, like Ibn Taymiyyah and Ibn Qudamah, who directly opposed the "foreign sciences." More recent thought has tended to moderate the emphasis on al-Ghazali, noting instead the conservative religious turn of the Seljuks and the Ottomans.

There is no final answer, in other words, on which historians fully agree. Internal and external forces played their part. What can be said with no small certainty, however, is that we are wrong to try and identify something innate in Islam, some essence or eternal inclination, that rejects scientific work and thought. For no less than 500 years, Muslim culture provided the most fertile fields for such work anywhere on earth, equal to the best of what China offered over the same period. We can only wonder – and perhaps this is a no less meaningful question, after all is said and done – how European science might have evolved without the transformative materials it hungrily accepted from the Muslim world.

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8 New World civilizations

Olmecs, Incas, Mayans, and Aztecs

> Here we shall write. We shall begin to tell the ancient stories of the beginning, the origin of all that was done . . . of all the sky and earth – its four corners and its four sides. All then was measured and staked out into four divisions, doubling over and stretching the measuring cords of the womb of sky and the womb of earth. Thus were established the four corners, the four sides, as it is said, by the Framer and the Shaper . . . of all creation. . . .
>
> Popol Vuh

These lines come from the Maya creation story *Popol Vuh*, a text that may originally date from before 600 C.E. The oldest version of it was written down in the highlands of Guatemala, sometime between 1554–1558, using the Quiché tongue, a Maya language still spoken by more than a million people. Later translated into Spanish around 1700, it is now available in many languages. *Popol Vuh* loosely translated means "Book of the Community." It is enormously important to the intellectual history of the Maya and Mesoamerica as a whole. This is because it preserves in some parts the actual words, names, and ideas from the time before any contact with Europeans.

The "four corners" in this passage are the four cardinal directions. We have seen that these were central in every civilization and here we see it again. Still more, the gods here are surveyors and geometers; they stake out and measure the dimensions of the cosmos, as if laying out a plot of land. As in the Old World, we find the universe created as a realm of mathematic order, assured by the power of number.

When we turn to the creation of the Earth and life, another striking fact greets us. Two gods come together to discuss how this should be done, Heart of Sky and Quetzal Serpent. Then "the germination and creation of the trees and the bushes, the germination of all life . . . in the darkness and in the night, by Heart of Sky, who is called Huracan."

Huracan, alias Heart of Sky, is the one god whose name is mentioned in every part of the creation. He has the creative power over all life and this suggests he has powers for its destruction as well. These powers reside in the core of the heavens, the "heart of the sky," which acts as a divine force of cyclic birth and destruction.

So we come to our own word "hurricane." Except that it is ours only in the sense of being adopted. Before any encounter with Europe, the word *huracán* was already in long use for many purposes, including the great swirling storms with an eye at their center. It first spread to Spain and then the rest of Europe, in a variety of spellings, from a 1535 work by the Franciscan Gonzalo Fernandez de Oviedo, *Historia General y Natural de las Indias* ("A General and Natural History of the Indies"). Within a few decades, it even appears in one of the mad rants by Shakespeare's King Lear (Act 3, Scene 2): "You cataracts and hurricanoes, spout till you have drench'd our steeples. . . ."

Each time we speak of such a storm, whether in ordinary talk or in meteorology, we call upon an ancient and complex history of association. It might be wondered, too, why we continue giving names to these storms, as if they were living spirits.

Background

New World civilizations are as old as any we have seen in the lands of Eurasia. Even if we focus on urban centers, with temple-like architecture, these existed in early form in Peru in 3500 B.C. An example: at the mouth of the Supe River, about 65 km (40 miles) north of Lima, such centers have been found at Aspero along the desert coast, and inland, at Caral, with much evidence of eager trade between the two.

Such findings have been confirmed only since the 1990s. But they have greatly changed views of New World peoples. For many decades, Meso- and South American civilizations were seen as far more primitive than those in Eurasia. As we will see, such is no longer the case.

Between the 4th millennium B.C. and the arrival of the Spanish in the early 16th century, the Americas saw a fascinating diversity of societies emerge. Unlike the other regions we have studied, these were the sites of hundreds of distinct peoples, languages, and cultures, many of which disappeared well before Columbus launched his little fleet into the Atlantic.

Archeologists have identified dozens of complex societies that helped develop shared forms of knowledge, which, in our terminology, approximate regional scientific cultures. The most sophisticated of these societies, with the most sophisticated science and technology, were the Olmecs, Maya, and Aztecs of Mesoamerica, and the Incas of South America (Figure 8.1). Each of these peoples developed the aspects of what archeologists consider "civilization": a complex social hierarchy; economic institutions; a defined political system; identified territory with one or more urban capitals; sophistication in the arts; high level of technology; highly productive agricultural systems. The earliest people to achieve all of this, the Olmecs, demonstrated such characteristics from about 1500 B.C.

New World civilizations differ from those we have discussed in certain ways. While highly capable in many areas, they remained dependent on Paleolithic technologies. They never invented the wheel, or if they did, they never used it for transport. Nor did they advance from copper metallurgy to iron. In fact, they

Figure 8.1 Map showing location and extent of the four civilizations discussed in this chapter.

rarely used metal for practical purposes, keeping it for ritual and decorative functions. Despite living near the sea, they seem not to have developed much maritime technology or trade until the time of the Incas (12th–16th centuries).

Yet it would be an enormous error to think such differences make New World civilizations less interesting from a scientific point of view. No one who has seen the ruins of Teotihuacan, a city of massive scale and precise geometry, which supported a diverse, multiethnic population of more than 125,000 in the 5th century C.E., would doubt the technical sophistication of the people who built it. The same is true for the cut-stone masonry of the Incas or the mathematical astronomy at Chichen Itza. Whether we are talking about the Olmec, Maya, Incas, or Aztecs, the engineering and artistry in their stonework never ceases to impress the modern eye and mind.

We may be tempted to view a good part of this as minor compared to what had been achieved in Egypt, Mesopotamia, or China. Yet there are two essential points to make about this. First, everything invented by New World peoples was indigenous, independent. For 5,000 years, the Atlantic and Pacific oceans acted as barriers to contact with the Old World. Thus, we might ask: which discoveries and technologies were shared by these two worlds and which were unique to one or the other?

Second, with the coming of the Spanish, everything was to change. Looking past the devastation this brought for a moment, we can say that, in scientific terms, this change was double-sided. There turned out to be a great deal Europe could learn from the Americas. From hundreds of new medicines to rubber to a realm of natural history that would forever alter the western view of life on Earth, technical knowledge flowed from the New World to the Old. Not a few accepted "facts" from the ancient Greeks were shown to be wrong. Aristotle's claim that the Earth's equatorial zones were too hot for human habitation, for example, proved a fiction. Ptolemy's *Geographia* was completely in error about the disposition of the Earth's continents and oceans. Indeed, what the Europeans learned from the Americas showed that classical authors were provincials. To say this played a significant role for the advance of science would be an understatement at best.

But if there were differences between the New and Old worlds, there were similarities too. New World civilizations were based on agriculture that, in lowland areas, developed along river valleys and in upland and mountainous regions, employed terrace farming. As cities developed, so too did irrigation, the building of canals, dams, and aqueducts. Society became divided into classes – farmers and laborers below, comprising the largest class, then artisans, soldiers, and merchants, followed by priests, and at the top the royal family. Governments relied upon a bureaucracy of civil servants and upon temple centers, in some cases extremely elaborate ones, to organize social, religious, and legal power. Cities had a market system, whereby food supplied by surrounding agricultural villages was exchanged for payment. Artisans, such as potters and jewelers, knew a great deal about the nature of their raw materials and developed technologies to utilize them. Physicians had high status, inherited their positions, and underwent rigorous training and education. While part of their work was to deal with possessing spirits and demons, they also had a professional knowledge of symptoms and diseases and considerable skill in using a great number of herbal medicines. If the Europeans persisted in calling New World peoples "savages," this had the distinct irony of applying equally to their own not-so-distant ancestors.

The Americas were the last habitable continents to be settled by humans. Though there are debated signs that people had crossed the Bering Straight as early as 35,000–40,000 years ago, those who archeologists call Paleoindians, the direct ancestors of the native American tribes that fully colonized the Americas first appear about 15,000–17,000 years ago with the earliest presence of humans in South America around 14,000 years before the present. These dates are not at all final, as new discoveries of settlement and human remains continue. However, it is apparent that the spread of humans throughout the Americas took place at an extraordinary pace, being largely complete in a mere 1,500 years or so.

In total, the time span from 7000 B.C. to arrival of the Spanish is divided into five periods. For the sake of our discussion, it helps to describe these briefly:

Archaic (7000–1500 B.C.). Early domestication of plants and a few animals, compelled by collapse of large-mammal populations due to over-hunting and climate warming. Many genera disappear by 9000 B.C., including mammoths from central and southern Mexico. By 3000 B.C., beginnings of actual cultivation take place, focused on maize.

Preclassic or *Formative* (1500 B.C.–150 C.E.). Increased cultivation of food crops leads to agricultural villages throughout Mesoamerica and parts of South America. Rapid development of some village networks into complex cultures, such as the Olmec, with regional centers and large-scale building by about 600 B.C.

Classic (150/250–900). Generally the highest state of development, especially in Mesoamerica, with more advanced technology, urban architecture, population growth, mature political and economic systems. Societies are stratified, with institutions justified by a system of ideas dominated by religion.

Early Postclassic (900–1250). Transitional period that begins with collapse of local and some larger cultures (e.g. southern lowland Mayan) and breakdown of *Classic* patterns of life. Migrations, conflict, fortifications, and increased urbanization occur, possibly related to a combination of militarism, resource exhaustion, and climate change (warming).

Late Postclassic (1250–1519). Expansion of military states and fortified communities that began in the previous period. Secularization now pronounced, with nonreligious authority common in political systems. There is the creation of large but short-lived empires, such as those of the Aztecs and Incas.

Our interest in scientific culture argues that we take a selective look at the four civilizations already mentioned, i.e. the Olmec, Maya, Aztec, and Inca (in chronological order). All shared certain fundamental aspects. An example is evident in their cities, which were mainly built out of stone, mortar, and plaster. Each civilization developed forms of monumental architecture and richly decorated their buildings with various types of artwork. Thus, knowledge about the properties of many Earth materials, as well as the quarrying, transport, and working of stone, reached particularly high levels.

How did the peoples of these four civilizations look at the world? Any direct comparisons with the Old World aren't likely to be much help. But we can at least say that the New World lacked a Buddha or Confucius. A pantheon of nature gods existed, with deities having both a benevolent and a destructive side. The universe ruled by these capricious powers was not gentle. Just as earthquakes, volcanic eruptions, and violent storms could bring sudden misery, so were the gods often resistant or even hostile to human welfare. In *Popol Vuh*, we read that the first generation of people created by the gods (made of wood) was inadequate and had to be destroyed in especially violent ways:

> There came the ones called Chiselers of Faces, who gouged out their eyes. There came Death Knives, which cut off their heads. There came Crouching

> Jaguar, who ate their flesh. There came Striking Jaguar, who . . . smashed their bones and their tendons. Their bones were ground up. They were broken into pieces. Their faces were ground up because they proved to be incapable of understanding before the face of their mother and the face of their father. . . . Their dogs and their turkeys said to them: "Pain you have caused us. You ate us. Therefore it will be you that we will eat now."

Such violent gods, it was believed, had to be appeased and nourished with human blood. Blood fed them and encouraged or even forced them to make the land fertile. As a result, the practice of self-bloodletting was widespread, especially for the aristocracy, who were believed to be closer to the gods. Blood was made to flow from the ears, tongue, or penis, using sting-ray spikes, a cord with thorns embedded in it, and other devices.

This brings us to human sacrifice, a feature of all four civilizations we discuss. Here is yet another difference from the Old World. Certainly ritual sacrifice took place there, too. We see evidence of it in Shang China, in the Old Testament (Abraham willing to sacrifice his son, Isaac), in the *Iliad* (Agamemnon sacrifices his daughter, Iphigenia, so that Greek ships can travel safely to Troy). Yet the ritual taking of life was so widely practiced in the pre-Columbian Americas as to seem almost endemic. In fact, the ritual differed a great deal between one time and people and another. The Olmecs seem to have performed it relatively rarely, in forms that perhaps included ritual suicide, while the Aztecs neared the other extreme, carrying it out on a daily basis, most often following the ancient practice of opening the chests of their sacrifices and tearing out the beating heart. So common did this become under Montezuma II (1466–1520) that it possibly installed a reign of terror. If the Maya, meanwhile, focused on animal sacrifice for part of their history, the Incas could choose their own children for sacrifice, singling out especially beautiful girls, who were prepared with special foods, including potato liquor and coca leaves (source of cocaine), dressed in beautiful clothes, and carried in litters to high altitudes and freezing temperatures where they were laid carefully in tombs.

Such practices horrified the Spanish. In Bernal Diaz's memoir *The True History of the Conquest of New Spain* recounting his adventures under Hernan Cortez, this horror runs through the book as a chilling secondary theme. Historians now believe Diaz exaggerated matters a good deal (he wrote the memoir decades afterward) but not entirely.

In fact, there is another dimension to the practice in Meso/South America. Art works, such as stone carvings and mural paintings, do not lack for images portraying gods in the form of animals (e.g. jaguar) eating hearts. But they also show the gods themselves suffering death, dismemberment, and decapitation. Mesoamerican nature religions held that the gods sacrificed themselves repeatedly, cyclically, to continuously bring life into being. To regenerate themselves and the cosmic order, they needed help from humans in return. Never-ending cycles of creation and destruction, birth and death, are involved.

Knowledge of the natural world, including its earthly materials, the stars overhead, and the great number of tropical and highland plants that covered it, therefore, provided its own important powers. As shown by the Maya, an ability to predict celestial movements, eclipses, the lunar cycle gave human beings the ability to understand and adapt to the order of the world, its cycles of time, and to gain some level of influence over the future. And more practically, as we have seen in every ancient civilization we have examined, the development of a scientific culture provided the essential material basis for many elements of cultural evolution, from the building of cities to the manufacture of clay for pottery or the selection of herbs for medicines.

Olmec civilization

Olmec is the name given to the most complex civilization of the Archaic and Preclassic periods. The level of development, compared to that of other peoples, in such areas as sculpture, artistic forms, and its system of proto-writing, was so much higher that some observers have proposed a direct connection to Asia. Scholars discount this idea.

Olmec culture emerged about 1600 B.C. among inhabitants of the Gulf Coast tropical lowlands in southeastern Mexico and lasted until about 400 B.C. The culture expanded over an area roughly 10,000 km^2 in size, including parts of the modern-day states of Veracruz and Tabasco. This portion of Mexico has a number of advantages that must have aided evolution of Olmec civilization. The area is a coastal lowland with a wet tropical climate, several major river valleys, fertile alluvial soils, an especially rich and diverse ecology, and a nearby upland with rock material for construction and sculpture.

Advantages of the setting helped secure and increase the production of food. The resulting increase in population led to one of the first real cities in Mesoamerica, San Lorenzo Tenochitlán. For reasons that are unclear, this city was abandoned around 900 B.C. and the heart of Olmec culture shifted northeast to La Venta, nearer the coast and along the Rio Palma River. A third urban center, Laguna de los Cerros, lay immediately south of the Tuxtla Mountains, a series of volcanoes and cinder cones last active in the late 18th century. Rock types from these mountains, including basalt, obsidian, and tufa, were abundantly used by the Olmec for building material, weapons making, religious objects, sculpture, and art works. Archeologists have determined that quarried stone was loaded on rafts and transported to urban centers using a network of rivers connected by canals. Smaller towns spread east to west across what is called the Olmec heartland and were linked to the major urban centers by trade routes.

One factor that makes the Olmec particularly significant is their considerable influence on later peoples. While some scholars have called Olmec civilization the "mother culture" of Mesoamerica, this is rejected by others as exaggerated. Still, it is evident that the Olmecs did set a number of major patterns regarding civilized life that later cultures absorbed. Such patterns included, for example: monumental architecture (large-scale buildings, including temple mounds and pyramids);

an extensive trading network, reaching into surrounding lowland and upland areas, allowing for the import of daily items, luxury objects, and also materials used in artistic and architectural production; highly elaborate artwork, involving both natural and mythical/religious forms, as well as abundant use of sculpture; sophisticated stonework in a diverse range of rock materials, above all basalt but also jade, greenstone, serpentine, and hematite; development of astronomy and a calendar.

The last major Olmec urban center was La Venta in northwestern Tabasco. This rose to prominence starting about 850 B.C. and became a complex of pyramids, open plazas, monuments, residences, and more. Given its early date, it must have been a marvel of art, engineering, and urban architecture. Nonetheless, La Venta was abandoned by 400 B.C. Why it went into terminal decline remains unknown. Violence seems to have been involved; nearly all the large altars, tombs, and monuments have been intentionally damaged, knocked over, some of them even buried.

Olmec writing: a scientific connection

One unique aspect of Olmec civilization that impacted other Mesoamerican cultures, including the Maya, was its writing system. Most archeologists now believe the Olmecs developed the oldest known orthography in all of the Americas.

In the late 1990s, two sets of discoveries established this idea. In 1998, a few kilometers northeast of the La Venta site, two fragments of greenstone inscribed with signs were found, plus a fist-sized cylindrical seal, fully preserved, dated about 650 B.C. When inked and rolled on paper, the seal produced the striking image of a bird "speaking" a series of signs. A year later, road builders in Veracruz State were quarrying fill when they found pottery fragments, figurines, and a tablet covered with signs. This serpentine slab, officially named the Cascajal Block, measures 36 cm by 21 cm (14 × 8 in.) and has 62 signs, which, upon close inspection, reduce to 28 distinct glyphs. A few are repeated in short groupings, with the whole having a consistent order of linear, oriented text. There is a clear connection with glyphs seen on Olmec monuments and artifacts. Tentatively dated at around 900 B.C. (such dating is uncertain, since the slab was taken from its original location), the Cascajal Block does not appear related to the seal glyphs. Neither set of symbols has been deciphered, with one important exception.

With the Maya writing system as a guide, archeologists concluded that the bird was saying the words "King 3 ajaw." The word "ajaw" means both "lord" and a date on the Mayan religious calendar. This was the calendar used throughout large portions of Mesoamerica, up to the Spanish arrival, and is in use today in some parts of Mexico and highland Guatemala. Sometimes known as the Mesoamerican Calendar, it is a unique mathematical creation intended as a timekeeping system.

In simple terms, the calendar combined two parts, one being the secular 365-day solar year, the other a ritually defined cycle of 260 sacred days. The solar portion was divided into 18 months of 20 days, with five days added at the end of the year. Superimposed on this annual cycle was the 260-day calendar. The origin of this cycle remains unclear; some scholars have proposed it corresponds with the orbit of Venus, which has a period of 263 days, but there is no consensus on this. When combined, the two cycles create a third cycle by aligning with each other once every 52 years. Meanwhile, each day in the 260-day cycle was labeled with a number from one to 13 and matched with one of 20 different names. The name "3 ajaw" refers to the third cycle of 20 days and to the final, 20th day in that cycle ("ajaw").

Together, the 13–20 system made for 260 day possibilities (13 × 20) and had both a cosmological and mathematical significance. The number 13 represented the number of levels in heaven, while 20 reflected the use of a 20-base number system throughout Mesoamerica, itself thought to be derived from the number of human digits. Each named and numbered day in the sacred calendar was associated with a particular providence or fate ("ajaw" seems to have been an indifferent day). Thus, as with Old World astrologies, aspects of a person's future in terms of good and bad fortune could be determined from their day of birth, as well as the birthdays and events of their parents' lives. Many choices in life, for individuals and the state, were decided on the basis of the calendar, therefore, including marriages, friendships, medical treatments, wars, ritual feasts, planting and harvest days, and so forth.

The cycle of 260 days has been interpreted in many different ways, with no final consensus. One view is that it represents the average number of days between the first missed menstrual period and childbirth. Another identifies it with one or more agricultural cycles. Astronomical interpretations focus on cycles related to Venus, e.g. its appearance as either the morning or evening star.

People of the rock

The great majority of artifacts from the Olmec civilization are stone sculptures and buildings, monuments, stelae, ritual blades, jewelry, and masks. We might note that the word "stone" is an artistic substitute for "rock," which draws attention to the material used instead of the form expressed. Let us, however, begin with form.

Olmec civilization is especially known for its remarkable stone sculptures, above all giant human heads (Figure 8.2). There are also huge throne platforms or altars; life-sized human figures (including infants); animals; human-animal combinations, especially mixing a jaguar and child; and human masks. Smaller figures, as well as the masks, were carved from jade and, less often, serpentine, and other materials. Some wooden carvings have been found preserved, suggesting that stonework developed as a technological advance related to new tools created through testing and trial-and-error experiment.

The colossal heads, which have drawn much attention, vary from 5–11 ft (1.5–3.4 m) in height and 6–40 tons in weight. A total of 17 have been found, all dating from before 900 B.C. As they are of adult men, show different facial and head-dress features, are quite naturalistic, and required much effort to create, archeologists generally believe they represent rulers who commanded their production.

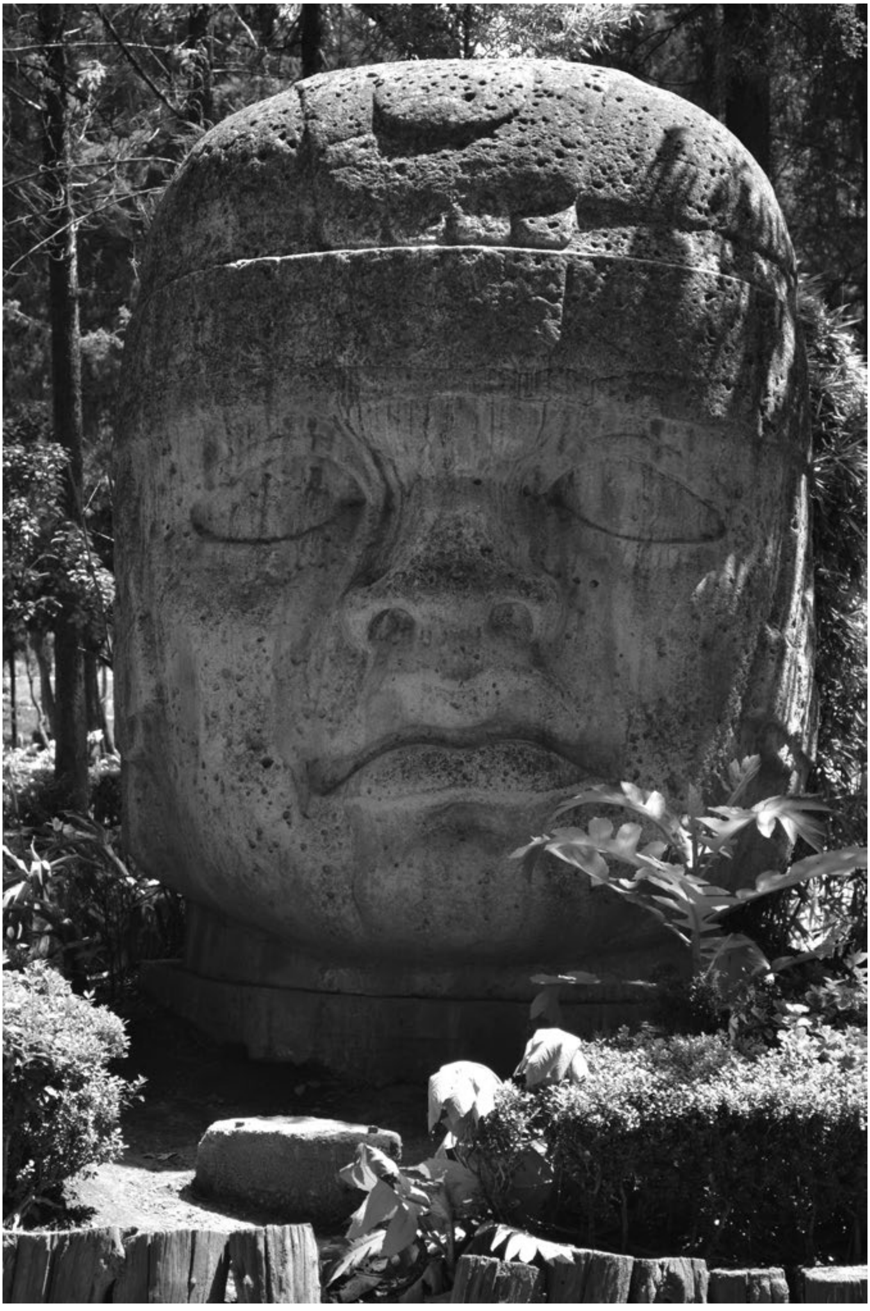

Figure 8.2 Example of the colossal stone heads carved from basalt by Olmec masons. This example stands over 8 ft (2.4 m) tall.

Turning from "stone" to "rock," we find that the Olmec were excellent students of local materials. This means they matched different rock types to different artistic forms, often systematically, other times on a case-by-case basis. Study of the surrounding region and comparison of rock samples has identified the Tuxtla Mountains volcanic complex as the source for the great majority of objects carved by the Olmec, including those at La Venta, more than 55 km (35 mi) away.

Nearly all the colossal heads are carved from basalt boulders that weathered out of massive volcanic flows and that have large mineral crystals in them, making them easier to carve. These boulders may have suggested giant "heads" in their natural setting. At the sites where they are found, some boulders show small or partial petroglyphs, indicating they were likely tested for carving. Detailed study of started and half-completed heads reveals they were worked in several stages: first, roughly shaped by percussion using perhaps fist-sized stones; next, refined into facial detail by use of hammerstones (cobbles, probably of similar basalt or quartz, attached to handles); finally, smoothed with abrasives, such as sand and rough-surface basalt. Boulders chosen for the heads were dragged or rolled downhill and then transported by sledge and raft to their destination, which might have been a carving workshop. One such workshop (Llano del Jicaro) just south of the Tuxtla Mountains has been identified. It suggests that a nearby urban center, Laguna de los Cerros, acted as a gathering and distribution center for carved or partially carved artifacts that were then finished at their final location.

Another important rock type found especially at La Venta are basalt columns 0.3 m (1 ft) in diameter or less. These were a primary building material, used as tomb enclosures, palisades surrounding ceremonial courts, entryway pillars, platform supports, and more. Hundreds have been found and probably many hundreds more once existed. They are natural, hexagonal columns (formed by the relatively undisturbed cooling of a thick basalt flow) that had to be carefully quarried. The closest source has been located along the northern coast of the Tuxtla Mountains, where columns could have been individually broken free, placed on rafts, and transported the 120 km to the mouth of the Rio Tonala River and upstream to La Venta. An important point is that these rocks are both distant and difficult to get to and thus suggest the Olmec systematically explored large parts of the Tuxtla Mountains for particular materials.

There is another dimension to this. Equally close to parts of the Olmec heartland and much easier to shape and carve are carbonate rocks that the Olmec did not use. The reasons why are not clear. Possibly, through observation, they understood limestone was much less durable in the wet, tropical climate. Yet there is another factor. During the period when Olmec civilization existed, there were active volcanoes in the Tuxtla Mountains. Obviously, these would have drawn much attention and likely became part of Olmec cosmology. For expressions of power and the sacred, rocks associated with this center of geologic action may have been much more suitable.

Finally, the more specialized use of other rock types strongly supports the idea that these people systematically explored their area, including the streams draining the Sierra Madre del Sur, south of their heartland area. To take only one example, they discovered here small blocks of ilmenite, a slightly magnetic titanium-iron oxide, as well as magnetite. It has also been proposed that the Olmec had at least one mining colony in the Sierra Madre del Sur itself where these rocks were extracted. Observing a metallic sheen on samples, the Olmec shaped them into ovals and circles and polished them into very high-quality mirrors, a practice well developed by 1000–950 B.C. Some of the circular mirrors are capable of igniting fires today.

Civil engineering

Olmec urban centers were built using several advanced engineering techniques quite remarkable in the Americas for their time. The two largest centers, San Lorenzo and La Venta, do not have city walls or other fortifications. Instead of large continuous cities, their development appears to be more like scattered hubs within an overall area of some extent. They seem to have been primarily made out of local earth, with stonework reserved for more special uses related to religious needs and political authority.

La Venta, founded about 850 B.C., is the less well-excavated and more disturbed site (it sits near existing oil fields, and portions of it have been built over by a local oil refinery). In total, it covers a large area, possibly 20 km (12 mi) in length, once containing a large-scale pyramid complex, vast open plazas, rectangular ball courts, and abundant stone monuments. These features are aligned with the long axis of the 20-km area. Archeologists interpret this axis as having been probably determined by astronomical phenomena (the pole star?), as it is eight degrees west of north.

San Lorenzo is the smaller of the two urban sites, covering about 7 square km, but far better excavated. It lies on a plateau elevated above the surrounding lowland, its urbanized portion showing extensive leveling that utilized as much as 2 million cubic meters of earth. This is a huge volume and indicates high-level planning and organized labor on a large scale. Just as impressive from an engineering point of view is the below-ground aqueduct system. Water supply on the plateau would have been variable, with the water table rising and falling on a seasonal basis. The aqueducts were fashioned out of basalt blocks, in which u-shaped channels were carved, with the front and back ends of each block flattened. The blocks were then placed into dug trenches, set into dense, wet, clay and pressed together, with clay smeared over any intervening gaps. Capstones were then placed over the blocks, sometimes with small altars or monuments attached. Sources of water for the system likely included artesian springs or shallow aquifers.

It appears that the highest stratum of society lived on the upper part of the plateau, with farmers and other commoners inhabiting the terraced slopes and surrounding lowland fields. Terraces were leveled out and then secured by retaining walls made of packed earth. These were extensive, running some distance around the plateau. Houses for the elite were built on raised clay foundations and had earthen walls, possibly created by a rammed-earth technique (earth placed between wood forms and packed down, layer by layer, with ram-like tools). These walls seem to have been covered with a red sand, produced by mixing regular grains of quartz with crushed hematite. Basalt columns up to four meters (13 ft) tall supported a combined wood-thatch roof.

The Stone Age never ended

Archeologists do not use the term "Stone Age" very much. They prefer Paleolithic, "older rock," to designate the period before metals were used, and also Neolithic, "newer rock," for when agriculture appeared. Perhaps, then, it makes sense to coin the term "Hololithic," for "entirely rock."

This is because the Stone Age is still very much with us. The relationship between humans and rocks has never waned or weakened. If we think that modern society has moved on from such direct dependence, we need to think again.

Specific examples help. Bricks consist of sand and clay, with some lime and iron oxides, all ingredients that represent eroded particles of rock. Cement? Lime and clay, the former derived from limestone. Mortar? Lime and sand. Stucco, plaster? The same, lime and sand. Glass? Melted sand. What about asphalt, covering hundreds of thousands of square km? Made of aggregate – sand, gravel, and crushed stone – plus bitumen, which we normally call "tar," derived from petroleum, produced from rock reservoirs. As for plastics, which saturate modern life from phones and computers to cars and contact lenses, these too come from petroleum, which was itself once called "rock oil." Uses of petroleum go even well beyond this: lubricants, clothes, inks, makeup, medicines (it is a terrible shame that we employ so much of it as fuel, which we just burn up).

If we turn to metals, we find, of course, that these too were originally rocks, "ore" we say. More exactly, they begin as various metal oxides or sulphides, in the form of minerals such as hematite (Fe_2O_3), cuprite (Cu_2O), and pentlandite (Ni,Fe)S.

We moderns are no less immersed in the world of rock than were the Mayans, Egyptians, Greeks, or even the Paleolithic hunter-gatherers who lived in caves.

Inca civilization

The Incas have often been called the Romans of the New World. Reasons for this include their historical role as empire builders, their huge program of road construction, their administrative talents, and their expertise in engineering, by which they brought to a peak technologies they both invented and borrowed.

As a distinctive people, the Incas were a Postclassic civilization. They emerged in the 12th century and thus came late to the long history of human settlement in

Peru. Their actual origins are unknown; many local cultures rose and fell, mixed and overlapped, during the millennia since civilization began in this region. Yet, because of record keeping by the Incas themselves and historical documents written by Spanish priests, some recording information from individuals alive before the Spanish arrival, we know a good deal about Inca society.

The Incas built the largest empire ever seen in the pre-Columbian times and amassed enormous wealth in the form of gold and silver. These riches were plundered by the Spanish and brought back to Europe, where they warped not only the existing economic system but the very idea of "wealth" – it would require Adam Smith to broaden this idea away from precious metals into its modern meaning. Far worse, however, was the systematic destruction of the Inca people, through war and disease, the execution of their leaders, and the wanton damage done to their records. In their ruin, the Incas served as an example to other European nations how "inferior" even the greatest states of the New World were by comparison.

The Inca empire began about 1438, when the ruler Pachacuti Inca Yupanqui led his soldiers out of the traditional homeland near the settlement of Cuzco to conquer areas north and south. Pachacuti was a remarkable military leader and ruler who turned Cuzco from a village complex into the capital city of a vast and expanding kingdom. He was the ninth ruler of the Inca people and seems to have had a sense of destiny. Later chronicles portray him as courageous in combat but still more, a leader who understood planning, organization, and the power of knowledge, including that of the heavens and of what we would today call civil engineering.

Expansion of conquered lands was continued and even accelerated under succeeding kings until an empire stretching from northern Ecuador to southern Chile was created, lasting until the Spanish under Francisco Pizarro destroyed it in 1532. The Inca Empire, therefore, lived for less than a century. Known to its inhabitants as Tawantinsuyu or "land of the four quarters," it came to extend more than 4,000 km (2,500 mi) and to be run, in part, as a military state. It may be difficult to accept that the Incas, as an ethnic group, never numbered more than about 100,000, yet ruled over an empire of more than 10 million. What this reveals, however, is that administratively they were very effective in getting other peoples to work for them. Part of this may have been due to military threat. But it is more likely that Inca rule brought certain advantages, in terms of protection, trade, technology, and amenities for local rulers.

As an example of their technical prowess, the Incas knit their empire together with 22,400 km (14,000 mi) of mostly paved roads, reaching from near sea level to mountain passes 5,000 m (16,500 ft) in elevation. The system upgraded any existing local roads and linked them into a network based on two major, north-south "highways," one of which ran for 3,840 km (2,400 mi) along the coast, the other through high mountain valleys and grasslands, from Ecuador to Argentina, a total of 5,170 km (3,230 mi), with many east-west routes connecting these two great threads. Most roads were paved with stone and, since wheeled transport didn't exist, were given steps on steeper portions.

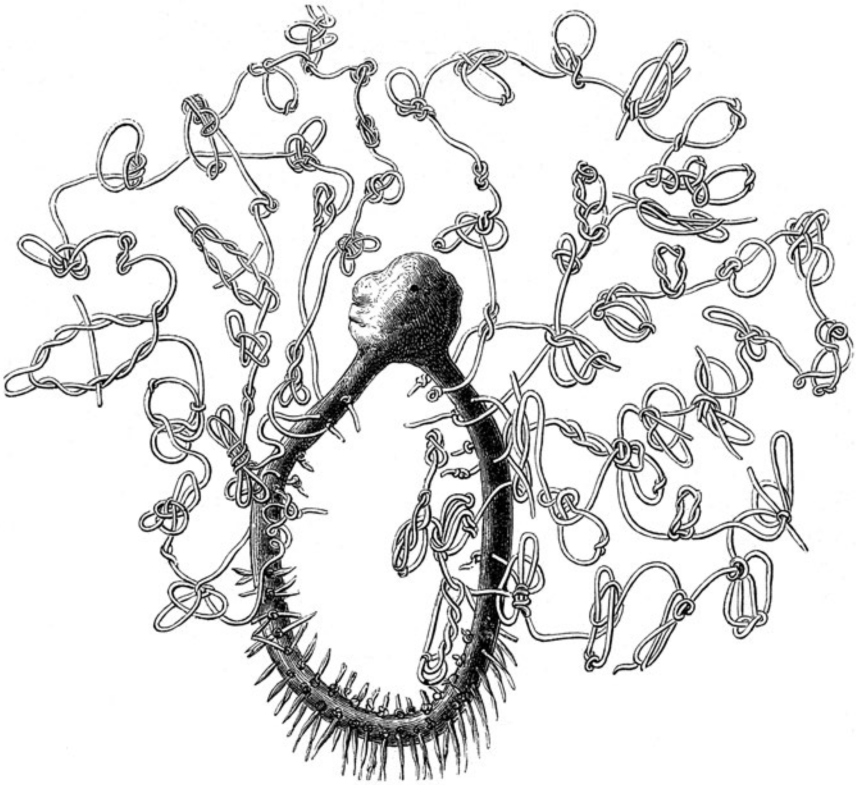

Figure 8.3 Example of *quipu*, the Inca system of visual communication using knots. © FALKENSTEINFOTO/Alamy.

Rivers were crossed by means of log bridges, while gorges were spanned by suspension bridges made of grasses and other plant material, requiring yearly maintenance. Nearly 2,000 "inns" were placed along the roads, as well. And just as it was once said that "all roads lead to Rome," so was this the case for the Inca capital, Cuzco, which lay at the center of the system, unfortunately enough. For just as it served the empire, the system provided ready access for the Spanish to all its cities.

Most archeologists of the Americas agree it is a bit of an exaggeration to say the Incas had a true system of writing, able to express everything that speech could in sounds. It is more accurately described as a scheme for recording accounts, harvests, genealogies, mathematical operations, and possibly more. The system is unique; there is nothing quite like it elsewhere. As shown in Figure 8.3, it is based on cords and knots, in the form of what is called a *quipu* (also: *khipu*). This involved a single main chord to which a number of other cords of varying color, bearing different kinds of knots at specific locations, are attached. Meaning is conveyed systematically by number of cords, cord length, color, type of knot (e.g. overhand, figure eight, multi-loop), knot direction, knot location, and other variables. The oldest *quipu* thus far found dates from around 650 C.E., proving that the system developed quite early and was employed for a very long time.

Material knowledge

More than any other native civilization in the Americas, the Incas understood the diverse uses for earth materials, stone most of all. Like the Olmec, the knowledge they assembled about different rock types was deep and detailed. Moreover, it was tested by nature itself. Several earthquakes in the 20th century, including one on May 21, 1950, shook the capital city of Cuzco, causing extensive damage to many of the modern and older Spanish buildings but little or none to the preserved Inca structures.

Through a combination of testing and experience, the Incas learned how granite, andesite, limestone, and other rock types could best be quarried and shaped. They observed and exploited the patterns of jointing (natural fracturing) in each type, the effects that different types of irregularities – veins, changes in crystal size, lumps of foreign material – could have on working the rock. Most of all, they became expert at understanding how different rock types responded to impacts, to being struck by hammerstones at various angles and levels of force.

This knowledge was given a tremendous boost by Pachacuti, the empire-builder. Upon coming to power, he commanded that the entire Inca capital, Cuzco, be rebuilt in stone. This meant hundreds, possibly even thousands, of buildings, as well as the paving or re-paving of streets, roads, and walkways. It would soon mean the building of fortresses, royal retreats, storage centers for food and weapons, all in stone. Very quickly, then, the profession of stonemason became one of technical expertise and status. Legions of stoneworkers were set to task, indeed many thousands, which called for high-level planning and organization.

Within several decades, a remarkable style of masonry was created, often called cut-stone. An example from Saksaywaman, a fortress site overlooking Cuzco, is shown in Figure 8.4. In this case, the basal walls are composed of gigantic stones reminiscent of the cyclopean blocks at Mycenae in Greece. But here, each block has been shaped in a precise way, transformed into a polygon that fits exactly with adjacent stones, to such a degree that even small, odd-shaped corners, lips, points, and notches are all perfectly accommodated. The stones have also been smoothed and partly polished, which enhances an image of power and control over nature. An early Spanish observer, Pedro Sancho, in 1534 commented that "neither the bridge of Segovia nor any buildings that Hercules or the Romans built are so worthy of being seen as this."

In mountainous terrain and without the wheel, the Incas were forced to make technical compromises. With few exceptions, they did not transport large amounts (or large-sized blocks) of rock far distances, as the Olmec did. In coastal areas, where rock exposures were less frequent, they manufactured adobe bricks out of local alluvial clays for building material. For towns and cities in the Andes, local stone was used, but this still meant that means of transport had to be invented. At one famous site, Ollantaytambo, considered the royal estate of Pachacuti himself, quarries were four kilometers away and a network of roads, ramps, and slides was

Figure 8.4 The classical Inca architectural style of polished cut-stone walls in which blocks of stone are tightly fit together without mortar.

used to transport roughly worked blocks. Red granite was the primary rock type chosen, but for a temple complex, blocks of rose-colored rhyolite (a volcanic rock) were selected. The major exception to local quarries was Saksaywaman, whose andesite stones came from quarries 35 km (22 mi) away.

Quarries were closely managed and much calculated work was put into planning and preparing transport of the stones. Special roads were built, kept to low inclinations, and supported by retaining walls several meters or more high, with in-filling behind them to create a consistent surface. Large retaining walls were also built above quarries to protect them from any rockfalls. The number of discarded blocks associated with some of the slides built to haul the blocks uphill indicates that stones could be damaged in transport and that quality was regularly checked.

How were these stones worked? What kinds of tools were used? Discovery of implements at some of the quarries has provided answers. The tools are simply rounded stones taken from nearby rivers but stones of significant hardness, such as quartzite, granite, and basalt, with smaller amounts of pumice for abrasion. Such hammerstones come in several sizes, reflecting different stages of work: larger stones for crude working and shaping, based on flaking (striking at an angle to break off large flakes); medium stones for cutting the surfaces; and small stones to finish corners and edges. Pumice was for polishing, when needed. It would seem obvious that masons experimented with different river cobbles to find the most efficient and durable.

No discussion of Inca stonework can ignore the spectacular, world-famous site of Machu Picchu (Figure 8.5). Its existence was first made known to western archeology in 1911 by the American explorer and archeologist Hiram Bingham, who was guided to it by local Quechua farmers. Machu Picchu was also built by Pachacuti, in 1470–1480, and is considered by scholars to represent the high point of Inca masonry and engineering. With a sophisticated aqueduct and drainage system, fountains, baths, terraced fields for farming, and more than 200 buildings, a number of them perched at the windy edges of high cliffs, supported by expertly built terraces, Machu Picchu has become the source of unlimited speculation about alien origins. Yet, from what we have discussed above, it is no surprise that such a site came from Inca stone engineering.

The location on a col between two peaks, plunging cliffs on its other two sides, was carefully selected undoubtedly on the basis of exploratory missions. Given its precipitous setting and limited space, scholars believe it was planned in great detail by high-ranking architects, who also directly oversaw its construction. At an elevation of 2,400 m (8,000 ft), high above the surrounding river valley, it is considered to have been a ceremonial center and royal retreat, having little military, administrative, or economic value due to its isolation. It includes some 200 buildings, including mostly residences, plus several temples, public buildings, and storage structures. Residences in groups of up to ten are

Figure 8.5 A view of Machu Picchu, a pre-Columbian Inca site located 2,430 meters (8,000 ft) above sea level.

gathered around central courtyards, with a large plaza extending through the center of the site.

The great majority of structures are made of the granite comprising the bedrock of the setting. While outer walls and terraces are made of more simply stacked stones, the precise cut-stone technique was used on building interiors. These inner-wall stones are smoothed and were originally polished. Their edges are all beveled, showing yet a still higher sense of artistry. A number of buildings make use of outcrops that have been carved and adapted to the plan of the structure. A striking visual aspect to the whole is the degree of integration between the landscape and the architecture – as if Machu Picchu has emerged out of the living granite.

Agronomy and more

Flat agricultural land was not abundant in the Andes. Moreover, many of the hillsides are not stable, being prone to rockfalls as well as mud- and landslides after heavy rains or melting snows. To address these situations, the Inca developed terracing to a new height, turning steep slopes into rich farmland over hundreds of meters of elevation. A good number of terraced areas are still used today.

Terracing is a complex, technical endeavor. It requires a survey of the stability on any slope – where the stronger and weaker parts are, where springs exist, where runoff goes after a rain, how thick or thin the soil is, the degree of fracturing in bedrock. All of these factors affect where and how a terrace should be built. The Incas appear to have treated each hillside as a system: where conditions were relatively uniform and water was easy to direct into irrigation channels, long and continuous terraces could be erected at equally spaced vertical intervals. In more complex settings, however, smaller sections of terrace were built in various patterns, e.g. rows arranged en echelon; rows that change height and width over different parts of a slope; rows with gaps. As for the method of construction, each terrace wall began about a half meter (1.6 ft) underground, where large, basal stones were laid as a foundation. Masonry above this consisted of stacked rocks, decreasing in size upwards, with the whole leaning slightly toward the hillside. Stacking was not tight and precise in order to allow for drainage.

But creating farmland needed soil. The fill behind the terrace wall was made up of stones and gravel, covered by local soil, which in turn was buried by several feet of prepared and selected agricultural soil. An irrigation channel was created slightly downhill from the base of each terrace wall, so that water would seep through the soil under the pull of gravity and then drain through the underlying fill. That this was done at Machu Picchu, a site where nearly every type of terrace mentioned can be seen, tells us a lot of lowland soil was hauled up the mountain. The large number of terraces here imply a planned ability for the king, court, and soldiers to remain for some time.

What was grown? Maize and potatoes were common crops. A more sophisticated, multi-crop system, known as *milpa* in Mesoamerica, was sometimes used as well. This involved first planting maize, followed later by beans, which would grow up the stalks, and finally squash in the remaining spaces. Inca farmers observed that the beans helped the corn to mature (they fix nitrogen, adding nutrients) and that the thick, low-level leaves of the squash would keep the soil moist and warm. In such conditions, terrace farming is able to nearly double the productivity of lowland farming.

What may be the most extraordinary feature of Inca agronomy is also the most enigmatic. This is the set of three circular terrace basins at Moray, roughly 50 km (31 mi) northwest of Cuzco. Each basin is dug into a low portion of an upland valley floor, giving the appearance of concentric rings from the air overhead. The largest and deepest of these consists of seven concentric terrace circles, overlain by five more that continue laterally into a bowling pin shape, creating a basin about 150 m (490 ft) deep and 300 m (1,000 ft) across (Figure 8.6). Amazingly, the temperature difference between the lowest and highest levels can reach as much as 15°C (60°F) – essentially one degree Celsius per terrace. Construction of the terraces is not like that at other Inca sites. Stones are often little shaped or not at all and are separated by packed red earth. Steps, reaching from the bottom to the top, are built into the sides of the terraces in several places, using flat-faced stones that stick out from the wall. Irrigation canals are also present. Finally, the whole structure fits into a natural bowl whose sides reach upward more than a hundred meters (333 ft) and thus effectively seal off the terraces from any winds.

The most probable plan behind this site, scholars theorize, is the creation of an agricultural experiment station (to use modern terms). The microclimate conditions,

Figure 8.6 Circular terraced basin at Moray, Peru. The set of three such basins at Moray are interpreted to be a possible agricultural experimental station for testing plants in different microclimates.

that is, would have been ideal to study the domestication, hybridization, and survival potential of various food plants at different simulated altitudes. A difference of 15°C is equivalent to climate temperatures separated by thousands of feet of elevation. Given the presence of irrigation canals, it seems obvious that Moray was used to grow crops. Study of the soils, the walls, the setting, and the structure of the site have yielded no definitive answers. But the uniqueness of the place, its protected setting, its size, its circularity (giving easy access to every square meter), and its remarkable microclimatic aspects continue to argue for a kind of outdoor laboratory.

Inca astronomy

There is a unique stone at Machu Picchu called the Intiwatana, the "hitching post of the Sun." It is carved from a natural peak of rock within the Temple of the Sun, near the very top of the site, at around 3,270 m (10,800 ft). It is a standing rectangle on a kind of platform, its two longer sides facing north and south, the shorter ones oriented east and west, with the whole tilted about 13° to the north. Shadows cast by the stone are distinct at the winter and summer solstices, and on two specific dates, November 11 and January 30, it has no shadow at all. Whether the Intiwatana was meant to track time by the Sun's position or to act as a more complex calendar is not known. Archeologists know that such stones existed in every Inca town, but (once again), they were destroyed by the Spanish, who associated them with the blasphemous Inca religion.

The link between the heavens and the Earth seems to have been as immediate for the Incas as it was for the early Chinese. But at high altitudes in the Andes, the stars and planets gained a brightness that they lacked even in the deserts of the Old World. There is some evidence that the capital of Cuzco, located in a fertile valley at 3,400 m (11,200 ft) elevation, was rebuilt under Pachacuti in a radial pattern, dividing the city into four quarters reflective of the four quarters of the empire and also divisions of the night sky. The avenues serving to create this division are associated with both earthly phenomena (springs, mountain passes, special rock outcrops, or monuments) and possibly specific risings of individual stars. To a degree, therefore, the actual layout of the city is an attempt to merge the terrestrial and celestial landscapes.

Heliacal risings were central to Incan astronomy. Stone pillars on the hills and slopes above Cuzco provided key time markers, such that the rising of the Sun between specified pairs of them signaled when the annual planting should begin at different altitudes. The appearance and disappearance of particular constellations, such as the Pleiades, also served to mark time. The Incas, in fact, had two different sets of constellations. One set was based on defined groupings of stars, as in other civilizations. But another set were identified as dark areas *between* stars, corresponding to what astronomer's today delineate as dark clouds of interstellar matter. These dark constellations were concentrated in the Milky Way and associated with specific animals, such as the snake, llama, toad, and fox, which they rule over. The Milky Way, meantime, the Incas saw as a great waterway mirroring the Vilcanota River, which ran through Cuzco, the center of Earth and Sky.

A true, official calendar was used at Cuzco. This was a 12-month lunar calendar, based on a sidereal month of 27 and 1/3 days, beginning on June 8 or 9 with the rising of the Pleiades and ending on the first full moon after the June solstice (winter solstice in the Southern Hemisphere). This meant, however, that the calendar fell short of the solar year by 37 days, which were added during different parts of the year on the basis of a "longer" summer or winter and the visibility of the Pleiades.

Maya civilization

The Classic era, particularly the period between about 250 and 650, counts as the high point of Mesoamerican development, when achievements in art and science rivaled those nearly anywhere in the world. This was a period when populations grew rapidly, cities multiplied, and enormous numbers of architectural structures were built.

At the peak of this development were the Maya. While some form of literacy probably existed throughout the region at this time, no other people developed such a complete orthography, nor, based on this, such complex astronomy, mathematics, and medicine. The Maya writing system was hieroglyphic; like the Egyptian system, it encoded the spoken sounds of the language but could be used to indicate a variety of separate meanings too. Nearly 800 individual glyphs have been identified. These glyphs included intricate, curvilinear forms that were carved in stone, painted on murals and pottery and also put down in ink on sheets of bark paper arranged as recognizable books.

The Maya, that is, were using a technology of paper-making. While it is not certain they invented it (though many scholars believe they did), the Maya certainly made abundant use of it. Called "amate" paper, it is derived from the bark of a species of fig tree (*ficus*). This was stripped from a trunk and beaten with special stones to make long sheets, up to 10 m (33 ft) in length, some 15–20 cm (6–8 in.) wide. These were then covered with a thin lime paste containing calcium bicarbonate, which helped to fix and smooth the surface. This was then folded in accordion fashion, sometimes called "screens," and painted on both sides. A wooden or hide cover was finally added. Texts could be read either fold-by-fold or else removed from their cover and spread out.

Archeologists estimate that there were once thousands of books. They also suggest this many works were needed to record a good portion of Maya learning. Contents of these books included histories, songs, prophecies, genealogies, ritual practices, ceremonies, as well as astronomical recordings, and possibly medical knowledge. Though the Maya civilization itself peaked well before the arrival of the Spanish, a great many books were still extant. Catholic missionaries, intent on converting the Maya, saw these works as demonic and so sacrificed them to the flames. The most zealous of these priests, Bishop Diego de Landa Calderon, wrote of his search for such texts in Yucatan:

> We found a large number of books of these characters and, as they contained nothing [but] superstition and lies of the devil, we burned them all, which

> [the native people] regretted to an amazing degree and which caused them much affliction.

Today, only four pre-invasion texts are known to have survived. They are known as the Dresden, Madrid, Paris, and Grolier codices (codex = sheets of paper bound into a book-type form), with the Dresden, dating from the 11th or 12th century, being the oldest.

Maya society, like nearly all Mesoamerican societies, valued its artisans highly, and this included scribes. In the creation story of *Popol Vuh*, the gods failed several times to generate beings who could speak their names and worship them, and this inability of their creations to produce language was critical, "for it is with words," they confessed, "that we are sustained." At the same time, to help mold such beings and thus complete Creation, the chief deities call upon the gods "Jeweler and Worker in Precious Stones, Sculptor and Wood Worker, Creator of the Green Earth and Creator of the Blue Sky, Incense Maker and Master Artist, Grandmother of Day and Grandmother of Light." Thus do artisans belong with the powers of fertility, weather, and time.

Geographically, Maya civilization included a number of different local peoples. These were divided between a lowland area, centered in the Yucatan Peninsula, a central area, that included Belize and northern Guatemala, and a highland area to the south of this, close to the Pacific Coast. These peoples were brought together by an increasingly common language and culture, one directly influenced by the Olmecs, as well as by other surrounding urban cultures, including the great city of Teotihuacan hundreds of kilometers to the northwest. Highland areas were sources of obsidian and jade, while lowland centers produced cotton, cacao, and other items for trade. Constant contact and communication between these areas aided the growth of a common culture. As the Maya grew in power and status, their language became a common second tongue for outside traders, merchants, and others. Yet Maya civilization was never a true empire. Instead, it approximated a collection of sovereign urban centers, among whom alliances could shift, break, and reform. As many as 40 such city-states were spread over the lowlands of Yucatan, Guatemala, and Belize.

The most rapid advancement, including scientific culture, was during the Classic period, from about 300–600 C.E. Before this, the southern highlands were most developed, as shown by their level of writing and art. But eruption of the Ilopango Volcano in El Salvador, starting about 250 C.E., seems to have driven a migration from many sites. Thereafter, Maya culture shifted more fully to the lowlands, where trade was extensive with other portions of Mesoamerica. Monumental architecture and elaborate tombs became cultural standards. Certain forms of art, such as figurines made from clay molds, came to be products of true mass production. Hieroglyphic writing had by this time become common on public buildings, altars, stelae, and in book form as well (though no such books are preserved from this period). Lowland cities grew in number and population, reaching a zenith around 600–700 C.E., when the total Maya population was possibly on the order of two million people. Most individual city-states probably never had more than

30,000–50,000 people, yet the larger metropolises, which often controlled many villages and village-complexes over an area as large as 200 km^2 (77 mi^2), could include up to 125,000.

Urban centers during the late Classic period could be epic in scale, sometimes approaching the monumentality of Egypt in the Old Kingdom. They included a ceremonial core made up of one or more pyramids, several large temples, palaces, royal tombs, and various smaller buildings, spread over several square kilometers or more. Material for such structures came from the ubiquitous limestone of the Yucatan carbonate platform, which is exposed near the surface in karsted layers and sinkholes. As is common in thick platform carbonate, significant amounts of chert and flint exist within the limestones and proved highly useful for stone tools. Each ceremonial core was part of a larger metropolis that also had dense habitation. There were many houses, palaces, and temples – places where various forms of contact with gods took place – as well as monuments built to honor rulers or to entomb them. At Kalakmul, one of the most powerful city-states, as many as 6,200 structures have been identified. The largest structures, such as pyramids and temples, bore the well-known steep stone steps and, originally, elegant decorations of bas-relief carvings, giant stucco masks, or brilliantly painted murals. The largest reached heights of 55 meters (180 ft) or more.

A majority of Maya were farmers in the immediately surrounding area. Artisans, however, were prized and kept busy by the large amount of stonework, sculpture, bas-relief, inscriptions, painting, jade carving, and more. Nearly every city-state also had a ritual ball court, usually placed in a large, open plaza where thousands could gather to watch. While the precise meaning of the games is still uncertain, they involved teams using hips, knees, and heads (no hands or feet) to direct a hard rubber ball through a vertical stone ring above head level. This was a ritual contest formalized by the Olmec but brought to a new level under the Maya. Winners were usually awarded rich prizes of textiles and jewels; losers sometimes became human sacrifices.

But where did the rubber balls come from? *Castilla elastica*, the Panama Rubber Tree, is native to tropical Mexico, including Veracruz, Central America, and northern South America. The sap is a natural latex and when blended with the juice of a species of Morning Glory vine (*Ipomoea alba*), which conveniently grew nearby and even on the tree itself, and then heated, the result was a liquid that could be poured into molds to produce rubber objects of excellent elasticity. This was known to the Olmecs as early as 1500 B.C. Discovered ball material shows beyond any doubt that the basic knowledge was already fully developed. Different proportions of the two ingredients allowed for later civilizations, such as the Maya and Aztecs, to engineer mechanical properties appropriate to other uses. Lab experiments performed in the 2000s have revealed that a 1:1 volume ratio of latex to juice yields a rubber with the best bounce (elasticity). A 4:1 ratio (25% juice) produces a particularly high wear-resistance rubber, which was used by the Maya and Aztecs for sandal soles.

Maya engineers were also highly skilled in methods for dealing with the supply, diversion, and drainage of water. In areas where near-surface water was lacking, they created many cisterns to store rain from the rainy season lasting intermittently from May to October. They also built stone canals for supply to people and for irrigation. In rainforest locations, where the challenge was sometimes to secure land from erosion, they created subsurface drainage and sewer systems able to accommodate huge flows during periods of heavy rains. Some of these systems employed the corbel arch (stones stacked with a progressive overhang until both sides meet), discussed earlier in our chapter on Greece. This architectural feature came to be applied to many major structures as well, like temples and palaces, to create hallways and doorways.

Competitive with each other from an earlier stage, the city-states began to engage in frequent bouts of war, disrupting trade, agriculture, and well-being. This seems to have intensified after about 700 C.E., when an extended period of serious drought occurred. Despite local expansions, no single city-state was powerful enough to conquer the others and create a kingdom. While the conflict between the two "superpower" cities of Tikal and Calakmul may have become central to this era, neither gained full control over the other. Indeed, military rivalry tended to debilitate them and those others that engaged in repeated wars. Possibly for these reasons and the drought itself, Maya culture went into decline. By the 900s, it had largely ceased to be a vital civilization. Around 1000, Toltec warriors invaded the Maya city of Chichen Itza, taking over its buildings and merging their own culture with that of the original inhabitants.

Archeologists concerned with the decline of the Maya now also point to the possible exhaustion of resources, due, for example, to over-cultivation of soils. These soils were not especially fertile to begin with, having most of their nutrients thinned away by tropical rains over many centuries. Another factor could have been water: in the Yucatan, where fairly thin soils exist above a thick limestone platform deeply eroded by dissolution, the water table is commonly 60 m (200 ft) or more below the surface. While the Maya built thousands of cisterns to store and provide water from the rainy season, this would be rather quickly exhausted in times of drought. Indeed, analysis of climate though the late Classic period suggests over a century of reduced rainfall leading up to, and including, the era of decline.

Maya cosmology and astronomy

Like other peoples of Mesoamerica, the Maya believed in a pantheon of nature gods whose presence and dynamism suffused all of space. The cosmos consisted of an underworld (nine levels), the Earth with human and animal life, and the heavens (13 levels). The Earth was the center of the material universe, and the gods spent much time on it, involved in the affairs of human beings. Therefore, their movements in the heavens were closely observed and recorded, so that important events such as a major ceremony or inauguration of a new ruler would coincide with a time when the gods were most favorable. Some Maya cities and a large number of buildings and sacred complexes were oriented to certain astronomical phenomena, such as the solstices. Here, then, we have another example of a tendency shared by early civilizations in both the Old and New Worlds, suggesting a profoundly human inclination.

As we saw in the opening to this chapter, the Earth was imagined as a flat space divided into the four cardinal directions. Added to this was a central axis that took the form of a great cosmological tree, the ceiba (silk-cotton tree). Roots of this tree were one set of paths for human spirits to reach the underworld and whose branches, reaching to heaven in the Milky Way, served either as another such road to the next life or as a great passageway for the gods to reach Earth. This fundamental spatial structure was used as the layout for Maya homes and fields. Houses were oriented by a pole in each corner corresponding to one of the four directions, with a fifth pole in the center where a domestic hearth was often built as well. Farmers, meanwhile, would place poles in the corners of their fields, which created a spatial center for planting and growing.

The Maya were particularly interested in certain celestial bodies – the Sun, Moon, Venus, and 13 constellations. Primary concerns were the measuring of time and the predicting of important events. These needs, which were as much religious as secular, led to detailed knowledge about the movements of the three main bodies, as well as solar and lunar eclipses, and, to a lesser extent, the periods of the other plants. Observations regarding Venus, bright stars, and clusters were heliacal, based on their seasonal rising and setting relative to the horizon. As early as the 2nd century C.E., various astronomical happenings, such as the conjunctions of planets and their appearance in one or another constellation, are recorded on buildings to mark events.

The Maya saw the night sky mainly in terms of animals and auguries. Those "wise men who study the heavens" were priests charged with noting and recording movements to determine time, not only for planting, ceremonies, and auspicious days, but also cycles of creation and destruction. Each celestial phenomenon was associated with an animal or person of some kind, as in other civilizations. Most important of all sky objects was the Sun, prime giver of life, depicted as a red eagle with a great, all-seeing eye. The waxing Moon was a young maiden, showing fertility, and an old woman, with powers over childbirth, when waning. Either the ecliptic or the Milky Way was a double-headed serpent, with the latter often called a white-boned serpent during the winter months, when it is especially dominant in the tropical sky. Maya constellations included such animals as a scorpion, bat, bird, turtle, wild pig, frog, jaguar, and fish-snake (shark?). Our knowledge of the Maya zodiac is incomplete.

Based on analyses to date of the Madrid and Dresden codices, information from post-Columbian texts, and also discussions with highland people who practice related traditions today, it is evident that the Maya developed a highly elaborate astrological system. As with other such systems, this made use of astronomical patterns that are quite complex, involving many different conjunctions of planets with each other and with constellations. In the case of the Maya, however, more extensive patterns involving intersecting centennial and millennial patterns for certain planets and stars have been proposed. Most such patterns remain to be confirmed.

One special constellation that bears discussion was the star cluster Pleiades, whose glyph was a rattlesnake tail. In the Preclassic and Classic periods, this rose in mid-May just before the beginning of the rainy season, thus marking the time for planting. The Maya also observed that the onset of the rains correlated with when the Sun enters the Pleiades, while the beginning of the dry season in November coincided with the Pleiades in opposition (on the opposite side of the sky) to the Sun. A related observation was Venus passing the Pleiades, which occurs between mid-March and mid-June, the period when the rains begin. The constellation was also interpreted to mark times of good fortune: a period of festivals, for example, was held when the Pleiades and Orion's belt rose at twilight and set at dawn.

What of the mathematical side to Maya astronomy? This took the form of arithmetic calculations for the most part, as the Maya did not develop geometry and, therefore, models of planetary motion. During the Classic period, priest-astronomers calculated that precisely 149 lunations (one full moon to the next) occurred in 4,400 days, thus producing an average of 29.5302 days per lunar cycle. When compared with the modern average of 29.5306, we find this was among the most accurate determinations made in the whole of the pre-modern period. Similar precision was devoted to Mars, whose orbit was recorded as 780 days, very close to the 779.94 number accepted today.

Venus, known as the "Great Star," was the third celestial orb to which the Maya devoted special attention. Careful tracking and recording of the rising, position, and orbit for this planet were deemed essential not only for agricultural reasons but because of a link between Venus and the Sun and thus major events. The planet had a powerful association with the sky god Quetzalcoatl (also: Kukulcan/Culcucan) whose birth and death cycle was represented by the change in Venus from morning star to evening star. Venus was interpreted to offer favorable signs for the timing of coronations and war. In the *Dresden Codex*, there are six pages taken up with tracing the position of Venus during the year, as well as predicting its future risings and settings. Seen from Earth, the planet's orbit around the Sun was 584 days according to Maya observation, extremely close to the 583.92 day period determined by modern astronomers (the true orbital period, viewed from Venus itself, is 225 days).

Still more impressive was the ability to predict eclipses. These were considered omens of ill and thus demanding of prediction. This was especially true of solar eclipses (as it was in other civilizations), which the Maya called *chi'ibal kin* or "eating of the Sun." To make such predictions, Maya priest-astronomers had to correlate the solar and lunar cycles quite precisely, which is more difficult than it sounds, since the plane of the Moon's orbit is tilted slightly more than 5° to the Earth's. Because of this tilt, the Moon's shadow at new moon (when the lunar body is directly between the Earth and the Sun) usually passes above or below the Earth. About twice a year, however, every 173.3 days, the paths of the Moon and Sun intersect and eclipses can occur. In the *Dresden Codex*, there are tables with eclipse predictions for every 177 or, in a few cases, 178 days.

Chichen Itza

This great urban center, which flourished from about 750 to 1000 as a Maya city and for another two centuries as a combined Maya-Toltec metropolis, constitutes the most world-renowned site in all of Mesoamerica. As in most Maya cities, some of the large structures here have been designed and built in accord with astronomical phenomena. However, such skill reaches a peak at this spectacular site in north-central Yucatan. There are subtle aspects to this design at Chichen Itza as well.

The site includes several major monuments: the Temple of Kukulcan, also called a pyramid and El Castillo (The Castle); El Caracol; the Temple of Jaguars; Temple of Warriors; and a large ball court. There is not space here to describe all these structures and their astronomical features, so we will focus on the two most significant.

The Temple of Kukulcan (Castillo) is in the form of a nine-level square pyramid. It has a total of 365 steps, exactly 91 on each of its four sides, and a final step to the top platform. Moreover, 91 days also separate the four stages of the solar year – spring and autumn equinoxes, summer and winter solstices. Meanwhile, on the spring and autumn equinoxes, a special, wavy shadow is produced at sunrise and sunset by the steps of the pyramid along the wall of the staircase. This undulating shadow continues from the top of the staircase to the base, where it meets the large head of a serpent that has been carved in white limestone. In fact, it is not the shadow that resembles the serpent but the portion of the staircase that remains brightly lit by the setting or rising sun (Figure 8.7).

Figure 8.7 Temple of Kukulcan (also called El Castillo) at the Maya complex of Chichen Itza. On each of the annual equinox, the flank of the temple casts a wavy shadow along the wall of the staircase, creating the illusion of a great serpent, ending in the head at the base. The effect is an excellent example of Maya knowledge and architectural use of astronomical phenomena.

Turning to El Caracol, this has more complex features, allowing it to be used as something of an observatory or "sighting center." Its grand staircase faces 27.5° north of west, which is out of alignment with the other buildings but lined up with the northernmost position of Venus. At the same time, the diagonal linking the northeast and southwest corners of the structure corresponds with the Sun when it rises on the summer solstice and sets on the winter solstice. At the top of the building is a circular tower with three windows, one wider than the others. The southernmost window aligns with magnetic south, the next window (to the west) with the southernmost position of Venus, and the third and wider window can be used to sight the northernmost position of Venus and the sunset at summer solstice.

Both the Castillo and Caracol also have orientations related to the solar zenith. As Mesoamerica lies in the tropics (between 23°N and S), the Sun occurs in a direct overhead, or zenith, position twice a year at noon. At Chichen Itza, the first zenith happens on May 25th, just before the rainy season begins and when planting takes place. The second zenith is on July 20th, which the Maya used as the first day of the ritual 260-day calendar. Castillo has its west face oriented at N69°W, or azimuth 291°, which corresponds almost exactly with the setting of the Sun on the day of the solar zenith. In El Caracol, there is a stairway niche whose wall has the very same alignment.

What does such astronomical architecture suggest about the role of the heavens and knowledge of the natural world in this society? In fact, the features we have mentioned are only part of the picture. There are others that have been identified for the Temple of the Jaguars, Temple of the Warriors, and even the ball court. The solar zenith is particularly important in this regard, as the interior of the temples is illuminated fully only by the sunset on the zenith days. Moreover, writing and mural paintings associated with these monuments deepen the astronomical symbolism by showing its relation to battles and other historical events – astronomy, in other words, becomes a telling of history (Maya history, of course), which, in turn, is shown to be the manifestation of cosmic unfolding.

That Chichen Itza has been interpreted in many ways, not least as a kind of observatory, is not surprising but may express more an attempt to cast this intriguing and enigmatic site in terms more familiar to the modern imagination. A different kind of possibility, suggested by our discussion of human sacrifice and its regenerative aspects, is that this site represents an effort of obedience and connection to the powers that govern all aspects of human existence.

Calendar and number system

Like nearly all Mesoamerican cultures, the Maya adopted the two-calendar system described above for the Olmecs, but they extended it as well. They did this by either accepting and formalizing a third time-reckoning method or inventing it themselves.

The three different parts to the complete system consist of the following: 1) 260-day sacred calendar, called *Tzolkin*, that included a cycle of 20 days that occurs 13 times, thus making 20 × 13 = 260 days; each day of the 20-day cycle was numbered from one to 13, in accord with each successive occurrence; 2) the 365-day civil calendar, the *Haab*, which consisted of 18 "months" of 20 days each, i.e. 360 days total, with five "inauspicious" days added (bad "destiny" to be born during these days), and finally; 3) a calendar known as the *Long Count* for determining dates within a cosmic creation-destruction cycle that began in the year 3114 B.C. In contrast to the *Haab* and *Tzolkin* calendars, the *Long Count* measures time in a linear way, using this counting system:

1 *kin*	= 1 day
1 *uinal*	= 20 days (20 kin)
1 *tun*	= 360 days (18 uinals)
1 *katun*	= 7,200 days (20 tuns) (19.73 years)
1 *baktun*	= 144,000 days (20 katuns) (394.52 years)

Thus, instead of a consistent 20-base system, the Maya shifted to an 18-base count for the *tun* division. Why? Because this is the length of the *Haab* year (before the five "unlucky" days are added), so there can be overlap between all three of the calendars.

Most monuments that have dates inscribed in them employ the *Long Count* calendar. A *Long Count* date is written in terms of the five units given above – for example, 2.5.3.1.4 means 2 *baktuns* (288,000 days); 5 *katuns* (36,000 days); 3 *tuns* (1,080 days), 1 *uinal* (20 days), and 4 *kin* (4 days). This would be followed by names from the sacred calendar to indicate precisely which day is meant. In our case, the total day count, 325,104, would be subtracted from the beginning date of the creation/destruction cycle (actually not agreed upon by scholars, but usually given as August 11 or 13 of the year 3114 B.C., using the modified Gregorian calendar) to get the indicated date in terms of our modern (Gregorian) calendar.

The beginning of the world and the creation of human beings appear to have occurred on the day 13.0.0.0.0, i.e. after 13 *baktuns*, or 1,872,000 days, had passed since the beginning of the previous cycle. Therefore, the same date corresponds with the final day of the *Long Count* cycle in which the Maya believed they were living. This was widely interpreted to be the winter solstice of 2012, which was Friday, December 21. As the end of the cycle, doomsday was supposed to occur, and many prophecies of this were made. Fortunately, as often happens, the end of the world failed to arrive on time.

To read a *Long Count*, we need to learn the Maya number system. As shown in Figure 8.8, it has only three symbols: a solid dot, for ones; a solid line, for fives; and – strikingly enough – a circular shell for zero. These were also given positional values, in a vertical sense (Figure 8.8). An example of how this was actually written in the Dresden Codex is shown in Figure 8.9. There remain, however, many unsolved difficulties about the exact interpretation of this extremely important document.

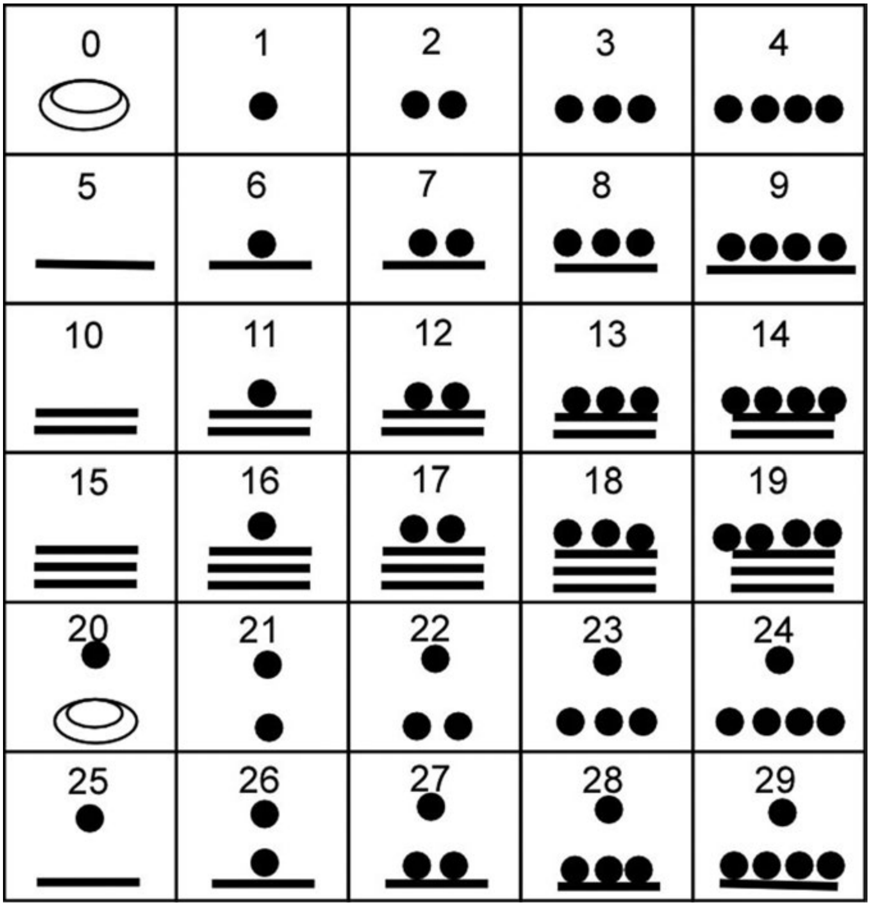

Figure 8.8 Maya number system, which included a (round!) zero.

Aztec civilization

Rising from obscure beginnings in the 12th century, the Aztecs came to create the largest empire in Mesoamerica, a spectacular warrior state that ruled over most of Mexico, including as many as 11 million or more people and many dozens of ethnic groups. They apparently began as an especially fierce and militarily skilled warrior clan who moved into the Valley of Mexico, an area of small city-states, sometime in the early 1300s. Under a powerful chief, Tenoch, they built a capital, Tenochtitlan (current-day Mexico City), on a small, swampy island in Lake Texcoco. Within a single century, it had become the largest city in Mexico. By the time that Hernan Cortez arrived in 1519, Tenochitlan had expanded well beyond the original limits of the island, drained all its swamps, filled in surrounding sections of the shallow lake, built canals and major causeways, massive temples, marketplaces, and urban infrastructure. Estimates state that the population

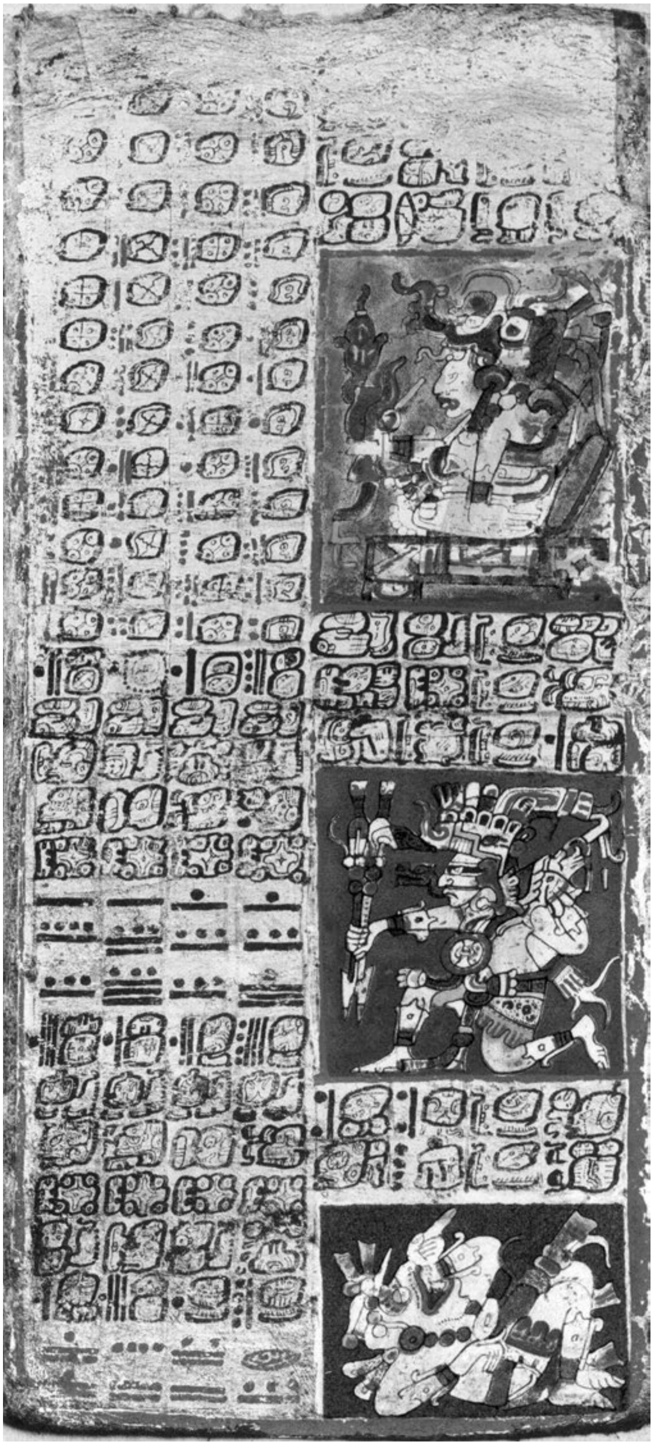

Figure 8.9 An image of a page from Maya Dresden Codex, a pre-Columbian Maya book of about the 11th century from Yucatecan Maya.

had reached more than 200,000 people, making Tenochtitlan one of the largest cities in the world.

The question has long absorbed historians of the New World: how did such an originally "primitive," rural people so quickly transform themselves into the urbanized rulers of an imperial civilization? In truth, there is no great secret here. We might recall that a very similar transformation took place in Islam, on a far grander scale. In both cases, a critical factor was the ability to absorb the achievements – above all, the scientific and technological capabilities – of older, surrounding peoples. For the Aztecs, this meant the Toltecs, an early Post-Classic people (9th–12th c.) who had themselves carried forward many aspects of more advanced Mesoamerican civilizations, including the Mayans. The Aztecs, in fact, revered all things Toltec, whom they viewed as their cultural fathers and themselves as their divinely chosen heirs. Great was the urge to create this mythic vision, to rewrite history in their own image. A direct and tragic result was the destruction of all the books from the peoples they conquered.

Major growth of the empire took place between 1440 and 1519. Indeed, it had expanded a great deal under its last emperor, Montezuma II (r. 1502–1520), and was in the process of continuing this when Cortez and his men first entered Tenochtitlan on November 8, 1511. As recalled by Bernal Diaz, the Spanish, after having seen many small, rural villages, were utterly unprepared for what they encountered:

> . . . when we saw so many cities and towns built in the water and other great towns on dry land and that straight and level Causeway [across the water] . . . we were amazed and said that it was like the enchantments they tell of in the legend of Amadis, on account or the great towers and temples and buildings rising from the water, and all built of masonry. And some of our soldiers asked whether the things that we saw were not a dream.

The legend of Amadis, meanwhile, from the book *Amadis of Gaul*, was Spain's own great tale of late medieval chivalry and knightly fantasy inspired by Arthurian romance (King Arthur and the Round Table) and one of the books that inspired Don Quixote to set forth on his adventures. It is not a little ironic to find it mentioned here, of course. Within a decade, the Spanish had leveled the city, reducing to their foundations all "the great towers and temples and buildings rising from the water."

What amazed the Spanish first and foremost was the civil engineering of the place: the number and scale of its structures, the causeways with removable bridges connecting it to land, the great aqueduct delivering fresh water, the masonry-walled canals running through the city and bustling with canoes (leading some to compare it with Venice), and the giant Tlatelolco marketplace filled with hundreds of stalls and tens of thousands of buyers and sellers, exchanging a bewildering array of goods, from foods, clothing, feathers, and tobacco, to pottery, jade, copper tools, and slaves. The city was built on a grid structure using the four cardinal directions, with the center temple complex facing due east to greet the rising Sun god Huitzilopochtli each day.

It is not generally known that the Aztecs were quite strict about law and order, education, and public behavior. This, however, is in keeping with a warrior society. Every physically able male was to serve as a warrior, even priests and merchants.

When born, a boy was told his family and house were not his real home, since his true purpose in life "is to give the sun the blood of enemies to drink, and to feed Tlaltecuhtli, the earth, with their bodies." The Aztecs practiced a form of baptism, to their rain god, using the 260-day sacred calendar for selecting a favorable day. Education for boys was focused on military training; for girls, song and dance seem to have been the primary subjects. Public drunkenness was not tolerated, except among the old. Excessive eating and bacchanalia in general were strongly discouraged. Thieves caught in the market by one of the monitors were beaten to death on the spot.

Disturbing to most modern readers is the obsession with blood that ran through Aztec society. The two sources of maximum glory for any man were to die on the battlefield for Huitzilopochtli and to supply captives for human sacrifice. A battleground soaked in blood was described as a "field of flowers," and the goal of any battle or attack was not just to kill the enemy but to capture as many of his number as possible for sacrifice. Only those who provided captives could ever rise into the warrior elite. Again, this was matched by the willingness of warriors to sacrifice their own lives in war, rendering them ferocious fighters.

Yet, the Aztecs were also the most sophisticated Mesoamerican civilization in terms of medicine. While their astronomy and mathematics were not at the same level as the Maya and other aspects of their overall scientific culture were derivative, their medical knowledge seems to have combined the best from other peoples and even advanced on its own. As a result, it is this area of science that we will examine.

To America from the Americas

The United States is considered part of European culture, defined broadly. This, however, means that it has absorbed many elements from Europe that, ironically, were imported from the Americas during the Age of Exploration. Many such elements became part of scientific culture in colonial times and even afterward. Here are some of the more well-known:

Guano: this nitrogen-rich material, derived from massive accumulations of bird dung, was a traditional fertilizer developed by coastal Peruvians and later incorporated by the Incas. The first European to document its use was the great natural historian Alexander von Humboldt, in 1802. Chemical analysis in the 1830s confirmed that plant growth depended on nitrates and phosphates and a global guano industry grew up, opening trade throughout the Pacific Basin and aiding the expansion of farming in Europe and America.

Panning for gold: Mesoamerican civilizations did not consider gold exceptionally valuable (textiles were worth more), using it as only one kind of currency. Instead of digging for it, they took it from river gravels, using placer mining. They used shallow wooden bowls, filling them with river sediment and water, tilting and shaking while gently washing away lighter material, thus employing knowledge of gold's greater weight. The process, documented by the Spanish, was later transferred to California.

Rubber: Production of rubber from plant fluids was 3,000 years old when Columbus sent back to Spain the first rubber balls in 1496. Spanish colonizers saw that set proportions of the two liquids were used to make different products, e.g. the soles of sandals, waterproofing for leather. They built a large export business in Mexico, with a major market in the U.S. A parallel industry grew up in Brazil, which became the world's largest supplier in the 19th century, until seeds of the rubber tree were smuggled to England and domesticated varieties were transplanted to British colonies in Malaysia, Sri Lanka, and Singapore. By 1920, these new areas had captured the global market.

Quinine: This vital drug was developed by Andean people that later became part of the Inca Empire. Derived from the bark of the cinchona tree, it was removed in strips, dried in the sun, beaten into a powder, and mixed with sweetened water. For centuries, it was a key medicine to reduce fever and chills. It became more important after Europeans introduced malaria to the Americas; it proved able to greatly reduce and even eliminate the causative parasite (*Plasmodium* protozoa). The Spanish imported it to Europe, and, in 1631, it saved many thousands of lives in Rome (then surrounded by marsh) and later cured Charles II (England) and Louis XIV (France). Quinine became one of the most effective medicines in Europe, a worthy substitute for leeches and bloodletting. Only in the 1940s was it finally superseded by new, laboratory drugs.

Petroleum: Before Columbus first visited Hispaniola or the Pilgrims landed at Plymouth Rock, Indians of western Pennsylvania had uses for oil. Surface seeps were found along a valley area later called Oil Creek. From the early 15th century, a branch of the Iroquois dug pits up to 6 m (20 ft) deep, lined them with timbers, and drew up the oil in pots and sealed baskets. They used it for fires in rituals, medicine for purging, a salve for sore joints, and mosquito repellent. The seeps became known to settlers and drew the attention of investors who financed the drilling in 1859 of the first oil well in the U.S. Though seeps were known for thousands of years in the Middle East, it was this well by Edwin L. Drake that proved the beginning of the oil industry.

Aztec medicine

Medicine practiced by the Aztecs was an alloy of religion and science, carried out by specialist priests who were not in any way involved in human sacrifice. Instead, as in other scientific cultures we have looked at, these priest-physicians underwent an extensive and rigorous training for healing. In this case, however, such training included a broad range of skills. Known as a *ticitl* or "healer" (a rough translation), the physician could also be called upon to perform as a soothsayer, a sorcerer, or a person of great wisdom. The *ticitl* could be either a man or woman but needed to come from a family of doctors. They needed to know the specific properties, growth habits, and medicinal effects of more than 300 plants, as well as how to prepare each particular drug or application. Yet they also had to be expert in the language of spirits and incantations and be conversant with methods of sorcery in order to protect a patient and undo spells.

Illness and disease, therefore, had three main causes. They could be sent as punishment by an offended deity, imposed by sorcery, or result from nature, which included both the interior of the body and the exterior environment. Like other warrior cultures, the Aztecs well understood wounds, bone breaks, organ damage, and many specific kinds of bodily trauma, as well as the phenomenon of infection. *Ticitl* were often skillful surgeons and had medicines to suppress infection and advance healing.

There was much knowledge of human anatomy, a conclusion scholars have made based partly on the rich vocabulary the Aztecs developed for internal features. This vocabulary, like the *ticitl* themselves, had no relation to ritual sacrifice. The body was conceived in some part as a microcosm of the universe, with various levels. The diaphragm represented the Earth, with everything above part of the celestial realm. The heart corresponded with the Sun, primal core of life, while everything lower down, including the abdominal area, reproductive and excretory systems, as well as the feet, were the bodily underworld in contact with the Earth's underworld forces. Each body was a specific convergence zone for external influences, some healthy, some not, some physical, others spiritual. At birth, each person is visited by a godly entity that emplaces a destiny of possibilities and inclinations. There were never guarantees of any kind; the gods who determined this destiny could be capricious, even vengeful. Children born with deformities, for example, were seen as the victims of goddesses who had died in their first childbirth and sought to spread their misery.

Within this overall system, health was defined as a harmony or balance among all the bodily functions, including the mental and spiritual ones. This meant, in effect, harmony of energy expressed, in one widely used scheme, as a normal balancing of heat and cold. Hotter parts of the healthy body, for example, included the head, heart, and penis, while the liver, abdominal cavity, and uterus were cold. Yet "hot" and "cold" were relative terms, in the sense that many gradations existed for both. Such classification allowed for a corresponding divisional scheme applied to disease. For example, there were hot and cold fevers (chills or no chills), circulatory problems, such as gout, that were cold or involved a progressive loss of heat. Illness or disease could be created from within or without. The latter could be brought on by sorcery, malignant spirits, or a number of other beings able to steal energy and heat, including humans such as albinos.

One interesting aspect to Aztec medicine, which the Maya also followed, is a great diversity of psychological illnesses. Some of these were based in fear or even terror generated in the person by outside forces, such as evil magic. Others, however, involved mental weakness and fatigue, associated with an inability to communicate with one's ancestors or the gods. Some of these illnesses were treated using hallucinogenic substances, more routinely used in religious ceremonies. In fact, there are at least a dozen plants whose leaves, roots, or flesh have some measure of psychoactive effect.

Medicinal plants formed the core of treatment for a great many conditions. It is thought that around 2,500 such plants were used to some effect across all of Mesoamerica, which would mean that, given the size of the empire, Aztec physicians could have had the majority of these available to them. Frequently used plants might be grown by the physician or in specialty gardens and sold in one of the great urban markets. Medicines could be made from leaves, flowers, stems, roots, sap, and bark. The knowledge embedded in the choice, preparation, and use of such medicines was obviously enormous and represented millennia of exploration, trial-and-error, and testing.

An example is the mixture of agave sap and salt commonly (and successfully) used on wounds to prevent infection. For head wounds, in particular, treatment involved cleansing with fresh urine from a healthy person (such urine is normally sterile), followed by application of a prepared paste made from sap of the maguey agave mixed with the herb *matlalxihuitl* (*Commelina pallida*), these two substances having the power to reduce or stem bleeding and to kill bacteria – effects that have been determined by modern laboratory analysis. Fatigue and gout were treated, with favorable results, by inhaling smoke from the plant *Nicotiana rustica*, a wild form of tobacco. Prescribed use included oral ingestion, often given with cacao or wrapped in flower petals to make taking it easier; fumigation; poultices; salves; skin rubs (for wounds, rashes, etc.), and more.

One particularly interesting example from the Aztec pharmacopeia is the wild yam sometimes called barbasco de placa (*Dioscorea mexicana*). The plant is inedible, with a thick tuberous root that forms a woody dome above the ground surface. Aztec physicians prescribed various preparations made from it to be used as a contraceptive for women, as an abortifacient (to produce abortions), and to reduce severe bodily aches due to rheumatism. For the first two uses, the *ticitl* would apparently mash the root, mix it with water, let it dry, and then grind it to a powder that would be taken daily. It turns out that the root contains a large concentration of diosgenin, a steroid. This was discovered in 1957, when the American chemist Russell Marker made a trip to Veracruz in order to collect and test samples of *Dioscorea mexicana*. He then founded the Mexican steroid industry, focused on the production of diosgenin for use in synthesizing progesterone – the steroid hormone involved in menstrual cycle and pregnancy. The industry employed a simple, inexpensive process that closely followed the Aztec preparation, except that the root-water mash was fermented for several days, breaking down the fibers, with the result then dried to produce highly concentrated diosgenin. At its peak in the 1970s, the industry had a labor force of more than 100,000 people, mostly Mexican workers, and was well on its way to depleting the plant in the states of Veracruz, Oaxaca, and Puebla. By 1980, however, still cheaper methods of progesterone synthesis had been found, bringing a rapid end to the Mexican industry. The story, however, gives us a potent example of Aztec medicines partially or wholly confirmed by modern scientific work.

The Franciscan missionary Bernardino de Sahagun was one of several Spanish clerics who lived in early 16th century Aztec Mexico and felt the need to record aspects of the culture even as it was being destroyed. Sahagun produced the most massive ethnographic study of the Aztecs (*General History of the Things of New Spain*, 1585; also known as the *Florentine Codex*), running to 12 volumes in modern publication. This work contains the largest coverage of Aztec medicine in any of these early writings, but it seems not to have had too great an impact in Europe, as it was not made publicly available. Still, Sahagun tells the story of Indian doctors tending to the wounds of Cortez himself and how well and quickly he healed. When Cortez later wrote to King Charles V about this, he made clear that these physicians were as good as the very best in Spain. Based on such reports, in 1570, King Philip II sent his personal physician, Francisco Hernandez, to Mexico for seven years in order to study the medicines and methods of healing. Hernandez compiled a vast work on Aztec medicine with many native illustrations and precise descriptions of therapeutic techniques. This book was brought back to Spain, where it had some impact. Tragically, it was destroyed by fire in 1671, though several sections of it had been copied and were preserved. A greater effect on European medicine, however, came from another Spanish physician, Nicolas Monardes, who wished to create a trade in New World drugs. In 1574, he produced a volume on these medicines that went through 50 editions, and was translated into Latin, Italian, and English.

Surgeons, meanwhile, worked on many types of wounds and fractures. They did amputations and made rudimentary prosthetic devices. They also employed splints and casts, made from cloth wrapping coated with lime. Still more advanced was the technique of using surgical pins, made of stone or copper, to hold bones together. Recorded by early Spanish observers, this represented a level of orthopedic surgery far in advance of anything in Europe at the time. Surgeons used human hair for suturing wounds. And they did dental work as well: large cavities were sometimes filled with small fragments of iron pyrite and dentures were made for the wealthy out of jade and turquoise.

Finally, we should mention, too, that Aztec medicine included common remedies that people used on their own. There were well-known and often-used ingredients for established therapies, in other words. Turning one last time to Cortez and his letters home to Spain, it is evident he was impressed with this aspect of Aztec society, to the extent of nearly admitting it was an equal to what could be found in Spain itself:

> There is a street set apart for the sale of herbs, where can be found every sort of root and medical herb that grows in the country. There are houses like apothecary shops, where prepared medicines are sold, as well as liquids, ointments, and plasters.

Yet, when he finally entered the Aztec capital, with all its wonders, Cortez found a large part of the people infected with smallpox, most of whom would die. The Spanish and the African slaves eventually brought over also imported measles, typhus, syphilis, and malaria. Advanced as Mesoamerican medicine might have been, it could not defend against microbes from other continents, from which the Aztecs and others had no immunity whatsoever. Since Columbus had first weighed anchor off Hispaniola in 1492, more than a dozen landings by Spanish ships had taken place in the Caribbean and nearby parts of Mesoamerica and South America. Rates of disease and death had soared. The epidemic brought by Cortez killed a third of the total Mexican population of 22 million by 1521. By the end of the century, barely two million would be left alive. The brutality of such numbers reaches far beyond any horror we might feel at human sacrifice. The end of Mesoamerica, as a center of purely native civilizations, was swift and merciless.

Concluding statement

It should be clear that applying the term "Stone Age" to Meso/South American civilizations is likely to create a misperception. These were complex, urbanized societies with a considerable depth of knowledge about the natural world and how to make use of it in sophisticated ways. Their civil engineering and architectural sophistication were close to that of the Hellenistic Greeks and Romans in many ways – a level, we might note, that was not re-achieved in most of Western Europe until the Renaissance. Their medicine, even including its aspects of sorcery, was much advanced beyond that of Europe, which stood in the shadow of the four humors until the 19th century.

Our coverage in this chapter doesn't do half justice to the scientific cultures of the pre-Conquest Americas, which varied from those of Arctic peoples to those of Amazonia. Instead, we have had to be more selective than in previous discussions. Yet there is an advantage to be found in this.

Much of this book is concerned with issues of influence. In the Old World, such influence began at a remarkably early date among profoundly different civilizations – between Mesopotamia and the Indus Valley, for example, starting in the early 3rd millennium B.C. By the beginning of the Christian era, Egypt, Mesopotamia, India, and China, as well as Rome, Greece, Persia, and Central Asia, had all been in contact to varying degrees, leading to the exchange of objects, ideas, knowledge, and technology.

Nothing like this took place in the pre-Columbian New World. Individual civilizations in the two main regions we examined, Meso- and South America, were generally quite small, localized, and close together during most of their history. Contact between Mesoamerican and Andes civilizations almost certainly occurred, based on the spread of maize to Peru (where it is not native) by about 2000 B.C. and, in the other direction, the probable transfer of metallurgy between Ecuador and western Mexico sometime in the late Classic period. These are certainly important exchanges. But they don't seem to indicate anything close to the continuous, ambitious trade maintained for many centuries between the Mediterranean, via the Persian Gulf, to India, or from China to Southeast Asia.

Early civilizations of the Americas, therefore, stand unique in their fertile isolation. This, of course, did not last. In our larger story regarding the history of premodern science, their importance rises when we consider their impact on Europe, as a new realm not just of "discovery" but of instruction.

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9 Inheriting and interpreting the world

The scientific culture of late Medieval and Renaissance Europe

> The ancients had only the books they themselves wrote, but we have all their books and moreover all those which have been written from the beginning until our time. . . . Hence we are like a dwarf perched on the shoulders of a giant. The former sees further . . . because of the stature of his bearer. Similarly, we [moderns] see more than the ancients, because our writings, modest as they are, are added to their great works.
>
> William of Conches, ca. 1130

William of Conches (c. 1090–1154) had been a student at the famous School of Chartres in France and sometime around 1120 he became a teacher there. His fame became such that he was called to be tutor to Henry Plantagenet, future King Henry II of England.

William was no ordinary scholar. Known to some as *physicus* (physician), due to his readings of newly translated Arabic works on medicine, he also wrote several books of philosophy. These had much that was new and some that proved troublesome. Rather than a traditional focus on theology, William devoted more space to the natural sciences, influenced by a major work by the 10th century court physician Ali al-Abbas al-Magusi and an *Introduction to the Practices of Galen* by the great 9th century Arabic translator Hunayn ibn Ishaq.

William's book, *Philosophia mundi* ("Philosophy of the World"), brought him some difficulty. He was accused of treating the Bible's Book of Genesis as more allegory than fact and of discussing "God as a physicist." These were comments issued by the powerful abbot William of Saint-Thierry, who had already convinced the authorities to condemn another great teacher, Peter Abelard (1079–1142), to perpetual silence. The *Philosophia mundi* was "pestilent venom," said Saint-Thierry; it must be purged.

It was not, however. Saint-Thierry's accusations were brushed aside as excessive and damaging to the reputation of the renown School of Chartres and the Chartres Cathedral, which was then in the final stages of being rebuilt. It could be said that the cathedral itself now argued on behalf of the *Philosophia mundi* author, given the appearance in its magnificent Royal Portal of sculptures of Aristotle, Ptolemy, Euclid, and Pythagoras.

William of Conches had a broader influence than just over his students. His statement about dwarves on the shoulders of giants – repeated by dozens of later writers, including Newton – he probably took from his own famous teacher, Bernard of Chartres (died about 1125). Yet in his own case, William was being too modest. He also wrote a well-known sentence of his own: "By the knowledge of the creature we attain to a knowledge of the Creator." It is our sign that a new door had been opened in European thought: seeking God through nature, instead of nature through God.

Background

Having now visited the scientific cultures of a dozen of the world's major civilizations, it is time to consider Europe as it approaches the threshold of modern science. To do so, we will be taking a somewhat different approach than in previous chapters. This will help to show that scientific modernity did not simply arrive on a winged chariot or emerge foaming from the sea like the birth of Venus, owing nothing to the millennia that preceded it.

Such was the view long held by historians. The centuries prior to when Nicholas Copernicus first touched pen to paper, that is, were considered little more than a long, dark night. With Copernicus, Kepler, Galileo, Descartes, and Newton, the dark ages came to an end, bringing to light the centrality of experiment, use of mathematics, and the scientific method. Summed up by Alexander Pope's famous lines: "Nature and Nature's laws lay hid in night/God said, 'Let Newton be!' and all was light."

Of course, this proved too simple by far. Though it persisted from the 19th into the late 20th century, it was eventually defeated by decades of scholarly work on medieval science and the impacts it absorbed from other scientific cultures, above all that of Islam. Today, a new view is in place. It is now possible – necessary, in fact – to speak of medieval science and its importance, as well as its relation, to modern science. One of the primary aims of the present chapter is to show that this is true. Let us then begin with the big picture.

Between roughly 1100 and 1550 C.E., Europe can be said to have undergone two full-scale transformations in scientific thought. The first of these, often viewed as a core part of the 12th century Renaissance, involved a translation movement no less momentous than the one that took place in Islamic culture and that was focused on the very same subjects. The movement, therefore, brought into Latin the combined legacy of scientific writings in Arabic and, to a significant degree, Greek. This meant, however, the substance of Islamic science and technology and, *therefore*, major portions of Greek, Indian, Persian and, to some extent, Chinese knowledge and invention. In its later stages, the translation movement turned more to Greek sources, most of which had been preserved (through copying) within Byzantium, though not enhanced by further scientific work.

Over a 200-year period, starting in the last decades of the 11th century and effectively ending by about 1300, Europe absorbed the world's most advanced mathematics, astronomy, physics, alchemy, medicine, engineering, and more. We find a similar overall pattern to what happened in Islam: an early focus on translation itself (the production of new texts), giving way quickly to the writing of original treatises, which, quite rapidly, became progressively more advanced and innovative. Enormous changes had to take place. A large-scale shift in scholarly circles from a traditional concentration on literary studies toward a greatly expanded interest in the natural world occurred. While resistance to such change was not lacking, it was local and largely ineffective. In 1210, 1270, and again in 1277, the Bishopric of Paris officially banned as heretical Aristotle's books on nature and any commentaries upon them. These condemnations had little real impact. Only a few decades after the last banning, the Council of Vienna called by Pope Clement V decreed professorships in Greek, Arabic, Hebrew, and Aramaic at the universities of Paris, Avignon, Bologna, and Salamanca.

Then, in the 14th century, there began in Italy a second transformation that soon extended to the rest of Europe. This was the Renaissance with which we are most familiar, a title created by the 19th century Swiss historian Jacob Burkhardt in his famous book, *The Civilization of the Renaissance in Italy* (1860). Burkhardt was concerned primarily with humanistic culture – art and literature, especially – not science. His view – and it is a view that has remained strong down to the present – was that these were the domains that broke with medieval traditions by finding inspiration in the forms and styles of ancient Rome and Greece. The Renaissance was also presumably the time when humanism was reborn, i.e. when European thought turned from a preoccupation with the divine and otherworldly matters to a greater interest in human life, agency, and experience. One of Burkhardt's main heroes was the Italian poet Petrarch (1304–1374), who inaugurated the term "dark ages" for the long period between the fall of Rome and his own time. Had he been more of a historian, however, he might have seen himself as part of something already underway.

It has been proposed, in fact, that the 12th century and the European Renaissances be understood as a single epoch, lasting some 450 years. Such would be comparable in length to either of China's two "golden ages," the Han and Tang-Song Eras, or Islam's "golden age." Looked at in this way, a similar period of progress for Europe doesn't seem exaggerated. Not all historians agree. Yet very few, if any, deny that something profound happened both in the 12th–14th centuries and the 15th–16th centuries.

We have seen that Copernicus made direct use of Islamic astronomy brought into Europe in the 12th and 13th centuries. No less, al-Haytham's book on optics wove an unbroken tapestry of influence that ran from Roger Bacon, John Pecham, and Witelo (13th c.), who all wrote on the subject, to Nicholas Oresme (14th c.), concerned with perception, then to Leon Battista Alberti, a mathematical theorist of perspective (15th c.), and to Kepler (17th c.). Ibn Sina's *Canon*, once translated into Latin, soon entered into the medical schools and onto the shelves of professional physicians and remained there through the Renaissance. William Harvey could still recommend a reading of it to a young student in the 1640s.

Yet such continuity was not the only pattern. Consider Albertus Magnus, the most deeply learned individual of the 13th century, with an encyclopedic knowledge of the sciences. Having absorbed the full impact of the translations from Arabic and Greek, he believed strongly that conclusions about phenomena had to come from actual evidence: "The goal of natural philosophy is not to accept statements from others," he wrote, "but to investigate directly the causes at work in nature." A thorough student of Aristotle, he was also critical of passages and ideas that seemed merely imitative. Albertus' thought was a stimulus to others well into the 14th and 15th centuries. And yet, ironically, his ideas on such things as minerals and mining became themselves overly authoritative, nearly gospel. It would require a true masterpiece of assembled knowledge, based on the empirical facts of long experience, to dislodge them. This was the part played, in the mid-16th century, by George Bauer, known as Georgus Agricola, in *De Re Metallica* (1546). The pattern here, from early example to frozen authority and finally new advance was repeated many times.

Historians have sometimes wondered why it took so long for a Copernicus to appear after the translation of Arabic and Greek texts. With so much new knowledge, how is it that major advances didn't come sooner? The answer usually given is that the new knowledge became, by the end of the 13th century, the subject of scholasticism, a fixed set of methods for disputation and study of texts, aimed at defending a focus on language and intellectual dogma. Scholasticism was a real phenomenon; there is no doubt. As we will see below, it could even affect the recording of observations, as in the case of Galen and anatomy.

Yet, it is easy to overlook the actual degree of change that was needed to build an entire new mind for science, so that a Copernican view could emerge. Scholasticism can also be seen as a period when the confining traditions of European education struggled to absorb the new knowledge on their own terms – and failed. Such failure, then, becomes a required phenomenon of its own. We can take it as a sign that there had to come a reorientation in the outlook of European civilization itself. This is what the building of a new scientific culture meant.

Perspectives

To understand the changes in Europe's own scientific culture that took place over the period we are discussing, it helps to look at a number of key themes. These show the varied dimensions of such changes, how they influenced different elements of scientific work, what they owed to the past, and in what ways they prepared the future.

The translation movement into Latin

Nearly the whole of Islamic natural science was brought into Latin during a movement that began just after 1060 and surged into the 12th century. As was the case in Islam, a number of factors came together to inspire a focus on philosophical and scientific texts. Such factors included increased trade and contact with Islam, newly conquered lands, particularly in Spain, and awareness of intellectual inferiority. But Europe was very different from Islam, too, and not just religiously.

By the 11th century, its culture was six centuries old and was entering a time of major social, technological, economic, and intellectual expansion. Among the larger changes were the rapid growth in towns and markets, replacing barter with currency-based buying and selling. There was a decided increase in water-powered machinery and use of the gear, allowing for mechanization of many industries (e.g. tanning, mining, shipbuilding). Also at this time was a growth in church schools; more students and teachers meant a significant increase in literacy, therefore, an expanded market for texts. There were new developments in theology as well, involving arguments over the value of reason and the role of doubt.

Lest we forget, too, the 12th century was the beginning of a major transformation in the arts, with scientific overtones. It marks the early Gothic era, when the first great cathedrals were built, with their embodiment of complex geometry and spatial relationships (the first being the abbey of St. Denis in Paris, dating from the 1140s). In the statues, oak leaves, and other carved stonework and in the illuminated (painted) margins of Gothic manuscripts, we see a striking new level of naturalism applied to earthly phenomena – to such a degree, that it is clear some of this work was actually drawn from life. Even objects as ordinary and small as insects merit such attention (Figure 9.1). Such little images, crawling across a notebook page or up the margins of a religious manuscript, give us windows into a transformation of interest in the natural world.

It was this setting of growing dynamism, reaching into every domain, that helped give rise to an interest in the superior scientific knowledge of Islam. Some indication of what was to come appeared as early as the 10th century in the life and writings of Gerbert d'Aurillac (946–1003), a scholar in astronomy and mathematics who later became Pope Sylvester II. Born in south-central France, Gerbert found opportunities to study under Islamic teachers in northern Spain. His writings include works on geometry and arithmetic, in which he even used the Hindu-Arabic number system (though lacking the zero). He also seems to have built astronomical instruments not seen since Roman times, such as the armillary

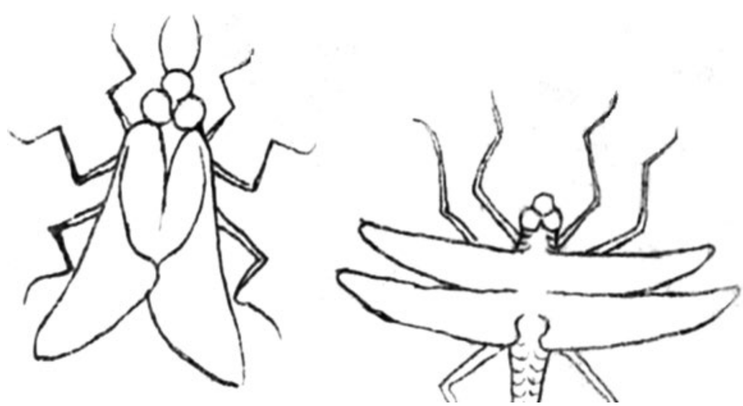


Figure 9.1 Drawings of insects from the *Sketchbook of Villard de Honnecourt* (c. 1220–1240).

sphere and a celestial sphere showing the stars (constellations). These achievements, however, did not have a lasting impact, perhaps because there were too few thinkers at the time able to appreciate their significance.

This was not the case for the first major translator of Arabic works into Latin, Constantine the African (also: Constatinus Africanus)(c. 1015–1090). Details vary on the life of this man, but it seems certain he began as a Muslim scholar from Carthage (Tunisia) and had learned Greek and Latin when young. It is said that he traveled widely as a merchant to locations as distant as India, then studied medicine in Carthage or Cairo and, reputedly, Baghdad. He then settled in the city of Salerno, a cultural crossroads in southern Italy. Having collected a large number of manuscripts on his travels, Constantine began his translation work there. He gained notice from the Norman rulers and established himself as a teacher before converting to Christianity and becoming a monk at the monastery at Monte Cassino, where he continued translating. In total, he rendered or paraphrased portions of perhaps 30 Arabic medical works, as well as portions of Hippocrates and Galen. Though the books of al-Razi and Ibn Sina do not seem to be among these, another highly useful text was, namely the *Kitab al-Malaki* ("The Royal Book") by al-Majusi (died c. 984). The works he translated became well-known in the 12th century and were responsible for generating a surge of further interest in Islamic medicine, as well as the philosophy and natural history on which it was based.

Such appetite was matched by a flood of further translations underway only a few decades after Constantine's death, by the 1130s and 1140s. Several important contributors to the movement are worth briefly discussing. The Englishman Adelard of Bath (c. 1080–1160) studied and taught in France before embarking, around 1110, on an exploratory voyage of seven or more years. He first went to Salerno, by this time a center of medical education throughout Europe, then to Sicily (another cultural melting pot), and from there to Syria, Palestine, and southern Turkey. Two of the books he brought back and translated into Latin were of huge importance: Euclid's *Elements* and al-Khwarizmi's *Zij al-Sindhind*. The significance of bringing Euclid into European mathematics should need little comment. Al-Khwarizmi's text, meanwhile, was the first ephemeris (table of positions for celestial objects) and also (re)introduced the Hindu-Arabic numeral system. He also wrote a number of original works on philosophy, arithmetic, astrology, the astrolabe, the abacus, and natural history, defending the use of philosophy and reason, advising his readers to interrogate the natural world through observation, experiment, and individual investigation, not by relying on what self-proclaimed authorities have to say: "For what else should we call authority but a halter?" he wrote. Adelard produced at least two versions of Euclid, one a full translation, the other more of a guide to Euclidian methods. There is also a third work, a commentary, that Adelard might have written. This might seem a bit arcane, except for one thing. Like the Arabic translators several centuries earlier, the Latinists decanted both the original works *and* helpful commentaries about them. Like al-Kindi, they wrote their own explanatory commentaries as well. This secondary literature had a powerful historical function: it greatly aided the understanding of difficult texts, like those by Euclid, Ptolemy, and al-Haytham, thereby advancing the overall process of absorption.

Adelard became another tutor for the young Duke Henry, future Henry II, king of England. At the beginning of his book on the cosmos and use of the astrolabe, *De opere astrolapsus* (c. 1150), he addresses the duke with these words:

> I thoroughly approve of the fact that the nobility of a royal race applies itself to the liberal arts. But I find it all the more remarkable that preoccupation in the affairs of government does not distract the mind from that study. Thus I understand that you, Henry, since you are the grandson of a king, have understood with the complete attention of your mind . . . that states are blest either if they are handed over for philosophers to rule, or if their rulers adhere to philosophy. . . . Hence it happens that you not only read carefully and with understanding those things that the writings of the Latins contain, but you also dare to wish to understand the opinions of the Arabs concerning the sphere, and the circles and movements of the planets.

Already 20 years earlier, when Adelard first returned to England, much of northern and central Spain had been wrested from the Moors by the kings of Castile, including the city of Toledo, a center of learning famous for its libraries bearing the larger part of Islamic scholarship. It was to this city that the greatest of all Latin translators came in the early 1140s, to hunt for a single book. Gerard of Cremona (1114–1187) was first educated in his home country of Italy but became aware of how weak his knowledge was of the sciences, astronomy in particular, when compared to what existed in Islam. At some point, while still a relatively young man, he made the decision to visit Toledo and learn Arabic so he could read and translate the "greatest work," Ptolemy's *Almagest*. This he did, but it proved only a beginning. Seeing the wealth of books on all subjects, so few of them able to be read by Europeans, he discovered his life's purpose.

Gerard spent the rest of his life in Toledo. We do not know where he lived or how. He may have been a teacher or a public lecturer or perhaps was paid for his translations. What we do know is that in the 40 years of his stay, he brought into Latin an astonishing number and diversity of scientific works, many of them surely challenging in their complexity. In total, he was responsible for some 70–80 translations. These included the *Almagest*, on which he continued to work until 1175; books by Archimedes, Euclid, Aristotle (seven different texts), Galen (nine); those by al-Farabi (three), al-Kindi (four), Banu Musa, al-Khwarizmi (his book on algebra), al-Farghani, Gerber, Thabit ibn Qurra (four), al-Razi (three), and Ibn Sina's *Canon*. This does not include nearly two dozen commentaries nor a range of other works that Gerard himself wrote. If he had done little else but translate the *Almagest* and Ibn Sina's *Canon*, Gerard would have done great service. His versions of these two works became so widely used as to be considered standard editions. But of course he did much more than this. We owe him even the trigonometric term *sine*, which came from the Latin word *sinus* (bay, pocket, hollow) that he used to translate this function from Arabic. As the medieval historian Charles Homer

Haskins once said: "More of Arabic science in general passed into western Europe at the hands of Gerard of Cremona than in any other way."

One last translator that deserves our special attention is the Flemish (Belgian) scholar and Dominican priest William of Moerbeke (c. 1215–1286). Almost nothing is known of his early life and education, except that he learned excellent Greek. As an adult, he seems to have traveled a significant amount, spending time perhaps for clerical reasons in Greece in the 1260s before being called to the pontifical court in Viterbo, central Italy. Perhaps because of his knowledge of Greece and Greek, he was sent as a participant to the Council of Lyons in 1274, an important but futile attempt to combine the Catholic and Eastern Orthodox churches. Following this, William was appointed Bishop of Corinth in 1277, where he remained, though with intermittent trips to Italy, until his death nine years later. At some point in the late 1250s, he embarked on the task of translating works by Aristotle, a project that subsequently turned into a program, possibly at the suggestion or request of Thomas Aquinas, whom Moerbeke likely knew. The program came to include Aristotle's complete works, as well as most of Archimedes, selected works by Ptolemy (the *Tetrabiblos*, an astrological work), Galen, Heron of Alexandria, plus commentaries on the more difficult of these works – in all, some 49 works. In some cases, he revised existing translations instead of translating them to produce a version he considered more accurate and reliable. Many of the original Greek manuscripts have since disappeared, and, without Moerbeke's Latin versions, the works themselves would be lost to us today. This was true of many other texts brought into Latin in the 12th and 13th centuries.

It is not known what William of Moerbeke's motive was for pursuing this work with such dedication for most of his adult life. A possible clue comes from the fact that he intentionally retranslated a number of Aristotle's best known works (e.g. *Physics*, *Metaphysics*, *De Caelo*) in order to replace existing versions. This strongly suggests that he saw his efforts as having a distinct historical importance.

These brief biographies, covering 200 years, highlight several major points about the translation movement in Europe:

- While it began with a focus on works in Arabic, over time there was a shift toward those in Greek. This involved a fair amount of retranslation, thus, in some cases, attempts to improve upon or simply replace what already existed.
- One reason for this shift was the perception that the Greeks were the primary source for most of Islamic science. This was joined by the traditional idea of *ad fontes* ("to the source"), granting ultimate favor to "original" authorities and the earliest commentators on them. Because of this, in part, there existed the view that Islamic thinkers had corrupted an original wisdom. This was a view that reached a peak in the 15th and 16th centuries. Despite this, however, a significant number of important authorities were Islamic early on.
- Aristotle, Galen, Ptolemy, Euclid, and, to a lesser extent, Archimedes were considered the most important of the Greek thinkers. Among Islamic thinkers, al-Kindi, al-Farabi, al-Khwarizmi, al-Razi, al-Haytham, Ibn Sina, and Ibn Rushd (Averroes) ranked particularly high.

- Extremely important was the role of Spain, which had been the site of the advanced al-Andalus culture. Spain boasted great textual centers; multi-ethnic, multi-lingual populations, including Christians and Jews as well as Muslims; and capable teachers. All of this was known and became available to Catholic Europe when Toledo fell to the Reconquista of Alphonse IV in 1085. But there were also materials that had been unknown to Europe but that spoke of the larger world, such as Sa'id al-Adalusi's book *Kitab Tabaqat al-Umam* ("Book of the Categories of Nations," 1068), which presents nothing less than a comparative history of scientific knowledge in India, Persia, Greece, Rome, Egypt, and the Middle East.
- In contrast to the movement in early Islam, where a large number of the translators were supported in groups by institutions, rulers, and private patrons, the Latinists worked mainly as individuals, earning their living as teachers, lecturers, and authors. Patronage was also important and came from a few wealthy individuals, from some universities, and from the Catholic Church. Some translators were themselves members of the church and received official encouragement for their work. Thus, another difference from Islam is that the translation movement did not face stern opposition from a significant portion of the religious authorities. Indeed, the Catholic Church acted more to assist and promote the movement.
- The translation movement changed the course of Europe's intellectual culture to its very foundations. As David Lindberg has nicely expressed it: "Western Europe had been struggling to reduce its intellectual losses; hereafter, it would face the altogether different problem of assimilating a torrent of new ideas." By the middle of the 13th century, this problem was being solved in many quarters, from art to mathematics. God, who had been earlier portrayed as a great and powerful presence in the heavens, motionless in majesty, now appeared as the active geometer and architect of Creation, using a compass to measure and craft its forms (Figure 9.2).

Leonardo of Pisa (Fibonacci)

Bridging the medieval and Renaissance periods is one of the most important mathematical texts written in the past thousand years. This is the *Liber abbaci* ("Book of Calculation", *not* "Book of the Abacus") by Leonardo of Pisa, also Leonardo Bonacci or Fibonacci (c. 1170–1250), which successfully introduced into Europe, once and for all, the Hindu-Arabic numeral system, including the zero, and how to use it in a positional, base-ten scheme. His book broke the tradition of using Roman numerals that Europe had continued, making impossible almost any form of advanced mathematics. *Liber abbaci* also introduced elementary and more advanced algebra; advanced (for Europe at the time) operations involving roots, arithmetic and exponential series; the Chinese remainder theorem, and much more. The story of this man, his sources, and his famous book provide an excellent example of what was happening in European science during this crucial period.

Figure 9.2 God the divine geometer, measuring out the cosmos in the form of a perfect sphere, as he creates it from an amorphous mass. Image is dated around 1230.

Leonardo was the son of an accomplished merchant who had been appointed trade representative for Pisa in the city of Bugia, located on the coast of modern-day Algeria. Bugia, in fact, was an ancient port town, used by the Romans, and later brought to important, bustling activity under the North African Islamic rulers. In the preface to *Liber abbaci*, Bonacci tells us his father "summoned me to him [in Bugia] while I was still a child, and having an eye to usefulness and future convenience, desired me to stay there and receive instruction in the school of accounting." Leonardo's father was an important man. At the time, Pisa was one of the more powerful Italian city-states, along with Genoa and Venice, that had established trading empires in the Mediterranean based largely on relations with Islamic merchants and local governments.

Given his duties and dealings in Bugia, it is fairly certain that Leonardo's father knew Arabic well. He was fully conversant with the number system used by Islamic merchants and the types of mathematical problems with which they dealt. As he had his son come and live with him, study with local teachers, visit and learn from the various bustling, international markets in Bugia, Leonardo would have gained the same knowledge. Like his father, he quickly grasped the tremendous advantages of the Hindu-Arabic number system, which he called *modus Indorum*. This, he said, made all that he had previously learned in European schools "almost a mistake."

Liber abbaci is a large work of more than 600 pages. It has three main parts: an introduction to Hindu-Arabic numerals and their use in arithmetic; elementary algebra and its relation to geometry; and mathematical applications to practical questions, mainly related to commerce. Much of the book is taken up with detailed proofs and with examples that are worked through carefully as completed exercises. As we saw with al-Khwarizmi's book on algebra, the effort is to teach actual mathematical logic – not just algorithmic rules but the process of finding solutions and constructing proofs. Indeed, it was the author's thoroughness and his inclusion of highly practical examples (as many as 90 in the chapter on algebra alone), that made the book so useful. Moreover, it is not all dry bones. Leonardo brings a note of humor into his examples: a spider, finding itself inside a cistern, tries to climb out; if it climbs a certain number of feet by day but slips back down a certain number at night, how many days will it take to escape?

As in Islamic works, algebra is presented in words, not symbols (symbolic algebra had to wait until the 16th century). Sections of the *Liber abbaci* were used as separate texts for school and university training for the next 250 years. What were Leonardo's sources? One of them was indeed al-Khwarizmi's volume on algebra, in Latin translation. But the others were Arabic texts on algebra and geometry that his knowledge of that language allowed him to choose.

Liber abbaci was among the first original works to come out of the 12th century Renaissance and have a major impact throughout Europe. That its primary source was over 350 years old, yet its author became a kind of celebrity for his innovative work, reveals two essential points: first, how much further Muslim mathematicians had progressed than their European counterparts; and second, how eager and capable European thinkers were to take advantage of Muslim achievements.

Universities

The change and growth of natural science in Europe is difficult to imagine without the university. This was a new institution that spread throughout Europe in the 12th and 13th centuries, that quickly gained a good deal of status, and that largely had control over the choice, repute, and distribution of texts considered essential to the well-educated mind.

Simply said, the university began as a type of "guild," a grouping of students and teachers into an official collective with legal rights. These rights were guaranteed in a charter issued by a ruler, a high-level church official, or the mayor of a town. A number of universities, in fact, were chartered by kings (e.g. the University of Salamanca by the Castile throne), a fact that indicates these were indeed high-status institutions. In turn, universities usually named themselves after the cities or towns where they held classes. Like guilds, they were self-determining; they had the freedom to choose their teachers, to set qualifications for admitting students and awarding degrees, and, not least, to decide the curriculum. Such protections were not airtight; the chartering rulers or bishoprics sometimes tried to change what was taught. Yet, as already noted with attempts at the University of Paris, such efforts either did not succeed or did so only temporarily. Use of Latin as the *lingua franca* for educated discourse meant masters and students could often move to other universities if they were dissatisfied or under attack.

To understand how transformative the university really was, it helps to know what was taught prior to its appearance. Recall that very little of Greek science and mathematics was adopted by the Romans and thus even less was passed on after the empire collapsed. This is crucial, because before the 12th century, the curriculum for an advanced education was based on the seven liberal arts, whose definition had been established in the final decades of the empire. These seven *artes* (subjects) were divided into the *trivium* (three parts), made up of grammar, rhetoric, and logic and the *quadrivium*, including arithmetic, geometry, astronomy, and music. Emphasis was on the *trivium*, concerned with the learning of Latin and uses of language in argument. The *quadrivium* was where study of science and mathematics resided. Much of this material was simple and elementary. Geometry consisted of a few definitions regarding lines and polygons, plus small amounts of geography. Astronomy was a mixture of very basic description, some definitions, names of stars, astrological discussion of the constellations, and, after the 7th century, the technique for calculating the date of Easter (the first Sunday after the first full moon falling on or soon after the spring equinox).

Given this, what kind of curriculum did the universities create? Detailed records, like syllabi, are rare, but we have indications that tell us about the more common works. The new curricula did not overthrow the *quadrivium* scheme entirely. They did replace all of its contents, however, while also expanding into wholly new areas. So much was this true that a teaching master of astronomy in the year 1050 would have been a source of some amusement to a second-year student at the University of Bologna in 1250. This was inevitable, since the new curricula were based on texts filling Europe's shelves from the translation movement.

Most courses were organized around the reading and debating of a particular text. Aristotle's works rapidly became essential, as did, in the medical curriculum, Avicenna's (Ibn Sina's) *Canon* and various works by Galen and Hippocrates. A list of books being used in courses in the late 13th century, especially in some of the larger universities such as those in Paris, Bologna, and Vienna, would include Aristotle's *Posterior Analytics*, *Physics*, *Generation and Corruption*, *On the Soul*, and *Meteorology*; Euclid's *Elements*; al-Kindi's surveys of Greek philosophy; Ibn Rushd's commentaries on Aristotle; and, instead of the *Almagest* itself, either al-Farghani's extensive digest of it or the simpler summary in *Theorica Planitarum*, whose author seems to have been the great translator Gerard of Cremona.

By the late 13th century, most major universities had faculties of medicine. More than a hundred treatises were in circulation by then for use in the medical curriculum. These included about 60 works attributed to Galen, another 40 attached to Hippocrates' name, five or six parts of Avicenna's *Canon* (studied separately), a work on surgery by Abbas az-Zahrawi, and encyclopedic works on medicine by al-Razi. Galen tended to dominate in medicine as Aristotle did in the regular curriculum. At the same time, as noted by historian Nancy Siraisi, treatises by Islamic authors were looked upon as valuable not just for their synthesis of Greek thought but for their own contributions and advances in the realm of therapy and their knowledge of herbal medicines. The writings of al-Razi, particularly his *Liber Continens* (*Kitab al-Hawi fi al-tibb*; "Comprehensive Book of Medicine"), were seen as especially worthy.

What we tend to find, therefore, is an impressive mix of material. Those who became "masters" (professors) of various subjects had the challenging task of selecting which new works to teach out of an ever-growing library of choices. Yet they also found help in various forms. Starting in the late 12th century but increasing rapidly thereafter, new works were being written by European authors. Al-Haytham's work on optics, for instance, was summarized into introductory works by both John Pecham (c. 1230–1292) and Witelo (c. 1230–1300), who fully accepted al-Haytham's theory of vision. These works became *quadrivium* textbooks for more than a century. But the most successful and well-known author of these kinds of books was John of Sacrobosco (c. 1195–1256). Based on lectures he was apparently giving at the University of Paris, this author produced two short manuals that soon became teaching standards throughout Europe. His first treatise, *Algorismus* (c. 1225) – the title a Latinization of al-Khwarizmi's name that helped establish the word "algorithm" – was based partly on Leonardo of Pisa's *Liber abbaci* and covered Hindu-Arabic numerals (Leonardo's book was not much used in the university curriculum, due to its focus on practical problems). A second work, *Tractatus de Sphaera* (ca. 1230), provided an introduction to astronomy that became one of the most widely used university texts in the whole of European history.

Within the curriculum, therefore, translated works, commentaries, and summaries by Islamic and European authors were typical by the mid-13th century. Over the next 300 years, secondary works by Europeans would replace those by Islamic thinkers. This, as well as the tendency of medieval authors to be quite selective in admitting their sources, weakened the role of Muslim thinkers in the curriculum. Aside from the two canonical authors, Avicenna and Averroes, many names of famous thinkers, well-known in the 1200s, drifted into relative obscurity three centuries later.

On the sphere

Among the European authors of new texts in science, few names were known so well to the first four centuries of university students as John of Sacrobosco. Nothing is known about his life. The only biographical details thus far concern the history of his books.

For two centuries, *Tractatus de Sphaera*, the most influential of his works, circulated through Europe in manuscript form before becoming one of the first scientific books to be printed in the 1470s, only a few years after printing houses began to appear (Figure 9.3). Dozens of print editions appeared, at least one in each of Europe's major university cities: Vienna, Venice, Paris, Cologne, Basel, Leiden, Antwerp, Wittenberg, among others. By the early 1600s, *De Sphaera* had appeared in more than 200 editions – more than one per year. Today, there are hundreds of copies preserved, an almost unheard of number for a non-biblical text.

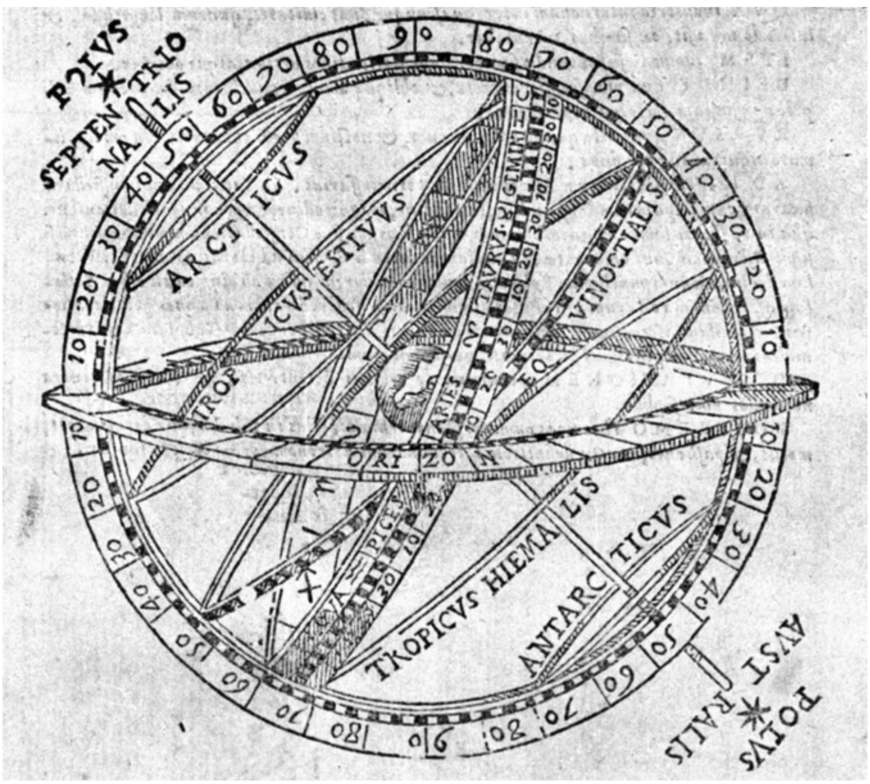


Figure 9.3 A late 15th-century printed edition of Sacrobosco's *De Sphaera*, showing a celestial globe with the Earth in the center and the ecliptic (apparent path of the Sun) shown tilted and including the constellations that the solar disk passes through during the year.

Some aspects to this book are revealing about science, in particular astronomy, at the end of the medieval period. The first two chapters cover definitions, then the sphere as the primal cosmic form, the heavens and their various parts, including the zodiac, and the Earth at the center. Chapter 3 is about celestial motion, risings and settings of zodiacal signs, as seen from different zones on the Earth, and the changing length of daylight. Chapter 4 finally introduces the Ptolemaic system for planetary motion. The length of Chapters 3 and 4 is revealing: Chapter 3 takes up nearly half of the book, while Chapter 4 is only a couple of pages. Celestial motions are really the core of the text, which is thus concerned with knowledge also highly useful to astrology. It also gives students what they need to know in order to use astronomical instruments, specifically the celestial globe and astrolabe. *De Sphaera* is thus not so much about theory but about how to actually witness the heavens. This is of no small importance, because it urges students to become observers before all else.

Something else about *De Sphaera* merits our attention. Consider this passage from Chapter 1, on the substance of the cosmos:

> The machine of the universe is divided into two, the ethereal and the elementary. . . . The elementary region, subject to continual alteration, is divided into four. There is earth, placed, as it were, as the center in the middle of all, about which is water, about water air, about air fire, which is pure and . . . reaches to the sphere of the moon, as Aristotle says in his book of *Meteorology*. For so God, the glorious and sublime, disposed.

Thus Aristotle is presented in service to the Christian God. But what kind of God is this, we might ask? A God who counts, who orders the cosmos by dividing it into two domains and four elements that (somehow) the ancient Greeks were able to discover. But there is a great deal more about Greek science that had to be made compatible in some way with biblical truth. *De Sphaera* does this by choosing to "explain," in its very last paragraph, the main astronomical event that took place during the Crucifixion, namely the darkening of the sky, which tradition held took place in the morning after a full moon:

> . . . when the sun was eclipsed during the Passion [Christ's crucifixion] and the same Passion occurred at full moon, that eclipse was not natural – nay, it was miraculous and contrary to nature, since a solar eclipse ought to occur at new moon or thereabouts. On which account Dionysius the Areopagite is reported to have said [that] during the same Passion, "Either the God of nature suffers, or the mechanism of the universe [*mundi machina*] is dissolved.

Sacrobosco uses a correct knowledge of astronomy to tell us why the loss of daylight at the time of Christ's crucifixion was a collapsing of natural law, a miracle. Rather than conflicting with the Bible's account, science is here invoked to newly "prove" its accuracy. Again, that is, we find that religion and science are not at all foes or opposites but colleagues.

There is yet another rich and revealing dimension to this brief work. This involves the authors that Sacrobosco has chosen to quote. They include astronomers (Ptolemy) and mathematicians (Euclid, Theodosius), naturally enough, as well as philosophers (Aristotle). But far more appearances are made by three poets: Ovid, Lucan, and Virgil. Sometimes a poet is used to reference Roman history, as when Lucan's *Pharsalia* (an epic on the civil war fought between Pompey and Caesar) is quoted to support the point of shadow differences between lower and higher latitudes. "You Arabs," says Lucan, referring to those who had come to aid Pompey, "have come to a world unknown to you/and marvel that the shade of trees is never leftward," i.e. purely west, since, at the latitude of Rome (~42°N), shadows always have a northern component. Another use of poetry connects with agriculture and the stars, shown when a quote from Virgil's *Georgics* is given: "First let the Pleiades, Atlas's daughters, set for you in the dawn/before you commit the seeds required to the furrows."

What was the purpose of this? These are poems and poets that students would have known. They, too, were part of the late medieval curriculum. Virgil and Ovid, in particular, were taught as examples of excellent Latin, models to help elevate expression in religious and other writings. Sacrobosco, therefore, is displaying a degree of learning that adds to his authority and connects with students. He is showing, as well, that great poets are themselves knowledgeable about astronomical realities and perhaps excellent observers too. From a modern perspective, we see other things: the lack of any clear boundaries between the arts and the sciences and the possibility for written science to include elements from many other disciplines, as we would call them today, such as history, geography, rhetoric, mythology, and, of course, poetry. *De Sphaera* shows us that the new astronomy could indeed be merged with existing medieval traditions of learning, at least at an introductory level.

Sacrobosco's work was commonly taught – and often physically bound together – with the *Theorica Planetarum*. As noted above, this was the truer digest of Ptolemaic astronomy and was studied after *De Sphaera.* No poets grace the pages of the *Theorica*. It is a concise work, derived from Arabic sources that covered Ptolemy's astronomy. By the 15th century, these two works had been the major texts in the basic astronomical curriculum for 200 years. To the most sophisticated astronomers, they were now hurdles to improved understanding. One such thinker was Georg von Peuerbach (1423–1461). Peuerbach noted the errors, gaps, and over-simplifications in the *Theorica*, and to remedy them he turned his own lectures on Ptolemy at the University of Vienna into a new work, *Theoricae novae planetarum*. Peuerbach's short and dense little book did indeed replace the older *Theorica* in the university curriculum and as such it was an important text for Copernicus in his own astronomical training.

The end of the circle

Copernicus is considered one of the greatest figures in the history of science. He is said to have begun the modern era in astronomy through his book on the heliocentric theory, *De revolutionibus orbium coelestium*, published in 1543. We know, of course, that he was not the first to propose such a theory.

Eighteen centuries early, Aristarchus of Samos had the same idea, as we have seen. His writings on the subject, however, are lost. Copernicus was aware of Aristarchus' idea, for he alludes to it in a brief section he decided to leave out of his book. Copernicus, therefore, did not invent but rather adopted heliocentrism, found that it worked better than Ptolemy's system, and provided a rigorous mathematical demonstration of this. It seems that he deleted his debt to Aristarchus, just as he might have to Nasir al-Din al Tusi. This might strike us as fairly damning information. Today, leaving out such debts would count as "scientific misconduct."

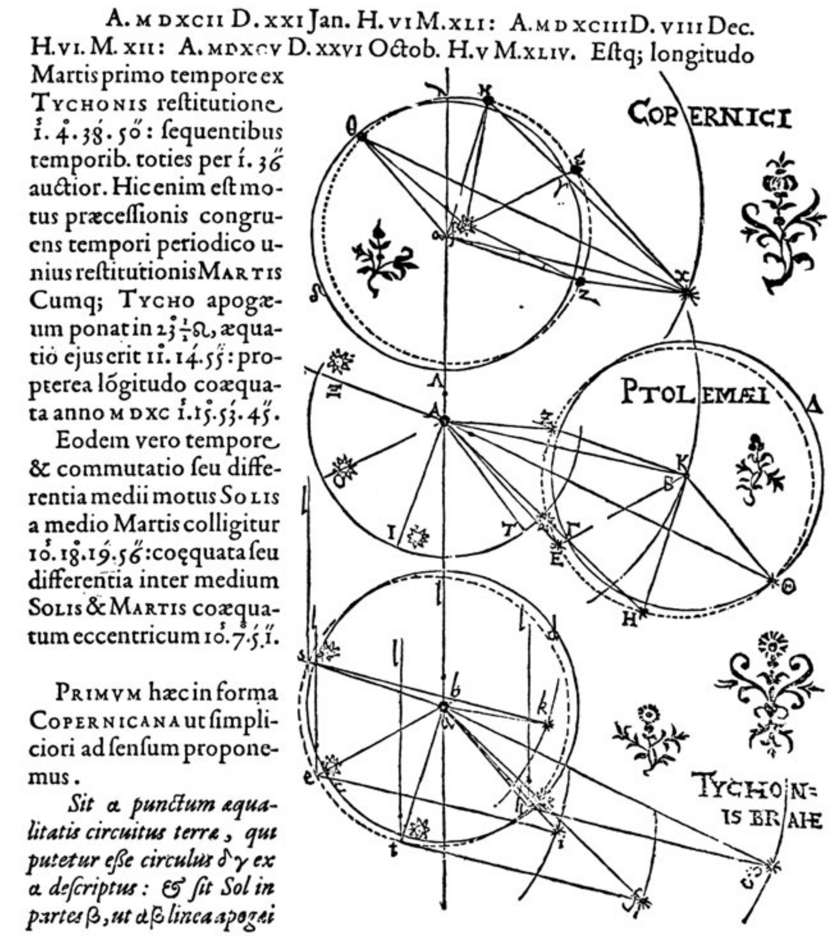
But in the 16th century, and also in the 17th and the 18th as well, this was typical. Writing a book for a large audience, the scientist needed to display learning but also, according to the terms of Renaissance achievement, originality. For *De revolutionibus*, the printer informs us on the title page that here are "new and marvelous hypotheses." Immediately below this is Plato's famous statement, in Greek, above the entrance to his academy, "Let no one ignorant of geometry enter here."

Many contemporary astronomers who read the book did not balk at its "new and marvelous" theory. What struck them most was how the author had done away with Ptolemy's equant, thus presented a simplified model. This might seem quite strange, until we note what Copernicus did *not* change—perfect circular motion of all bodies, the very ideal the Ptolemaic system was invented to preserve! Such was the view that had lived since Plato, a view strengthened by Aristotle, and that had its feet in Greek ethics and morality (see Chapter 5).

One of the most eminent defenders of Copernicus was Johannes Kepler (1571–1630). Though he accepted his predecessor's placement of the Sun and planets, he understood better than most what had been done and not done. Copernicus, Kepler wrote, "strives to outdo Ptolemy in the uniformity of motions." It was, in fact, Kepler's book *Astronomia nova* that destroyed the Ptolemaic system once and for all (Figure 9.4). After 10 years of wrestling with data on the orbit of Mars, Kepler came up with his first two laws of planetary motion: 1) the orbit of a planet around the Sun is not a perfect circle but instead an ellipse, with the Sun at one of the two foci; and 2) the velocity of a planet in its orbit is (not at all uniform but) variable, such that a line joining the planet and the Sun sweeps out equal areas in equal lengths of time. Kepler had preserved some level of "perfection," then, but the circle as the model for all celestial motion was no more. Who, then, was the greater scientific revolutionary?

Science and art: a many-splendored marriage

Historians have come to understand this truth about the Renaissance: that many of its most profound achievements in art and science owed a great deal to a mutual dependence between the two. What does this mean?


A. M DXCII D. XXI Jan. H. VI M. XLI: A. M D XCIII D. VIII Dec. H. VI. M. XII: A. MDXCV D. XXVI Octob. H. V M. XLIV. Eſtq; longitudo Martis primo tempore ex Tychonis reſtitutione 1. 4. 38. 50: ſequentibus temporib. toties per 1. 36 auctior. Hic enim eſt motus præceſſionis congruens tempori periodico unius reſtitutionis Martis Cumq; Tycho apogæum ponat in 23½ ♌, æquatio ejus erit 11. 14. 55: propterea lõgitudo coæquata anno M DXC 1. 15. 53. 45.

Eodem vero tempore & commutatio ſeu differentia medii motus Solis a medio Martis colligitur 10. 18. 19. 56: coequata ſeu differentia inter medium Solis & Martis coæquatum eccentricum 10. 7. 5. 1.

Primvm hæc in forma Copernicana ut ſimpliciori ad ſenſum proponemus.

Sit α punctum æqualitatis circuitus terræ, qui putetur eſſe circulus δγ ex α deſcriptus: & ſit Sol in partes β, ut αβ linea apogæi

447.31 KEPLER: ASTRONOMIA, 1609.
Credit: The Granger Collection, New York

Figure 9.4 Page from Kepler's *Astronomia nova* (1609), with a diagram comparing the motion of Mars according to the systems of Copernicus, Ptolemy, and Tycho Brahe. Kepler dismisses all three systems because of their dependence on circular motion, though he accepts the position of Mars given by Copernicus. © The Granger Collection/TopFoto.

Let us take art first. Starting in the early 1400s, mathematical ideas and techniques were developed that greatly advanced the ability of artists to portray the external world. Most important was the technique of linear perspective, by which the space in a painting could be precisely organized and mapped to simulate depth in three dimensions. The technique utilizes visual "rays" drawn to converge at a single "vanishing point" on a horizontal line. These rays would be parallel in real life but are drawn as diagonals to create the sense of depth on the plane of the picture (imagine train tracks running to the horizon). With such a system, artists could size and shape objects guided by these diagonals, e.g. be made proportionally smaller toward the vanishing point to give the illusion of distance.

Linear perspective was invented in the 1420s by the Florentine sculptor and architect Filippo Brunelleschi (1377–1446). Some scholars have argued that the invention was more a rediscovery from Greek and Roman art, yet there is no documentary evidence for this. Viewed from the history of science, it is far more likely that, as an actual *mathematical system*, linear perspective was developed in Europe. Why? Though Brunelleschi never published his idea, one of his colleagues did, the artist and mathematician Leon Battista Alberti in his book *De Pictura* (1435), which had an enormous impact on Renaissance art. Like every other thinker on vision at the time (including Brunelleschi, in all likelihood), Alberti was strongly influenced by theories of optics, including Roger Bacon and Witelo, but above all, al-Haytham. Al-Haytham's book on optics, translated as *De aspectibus*, by the mid-13th century had made obsolete the treatises by Ptolemy and Euclid and remained the standard work on the subject until Kepler. Bacon, as a "modern" authority, was strongly persuaded by the concepts of light traveling to the observer and of the visual field as a pyramid, obeying geometric laws. In his book *Opus majus* (1267), the chapters on optics refer constantly to "Alhacen" (Alhazen) and also argue that optics and geometry should be studied by every artist.

Alberti's *De Pictura* set the art community of Florence on fire. Paintings based on the techniques of linear perspective began to appear in large numbers and soon commanded the field, such that, by the 1480s, Leonardo da Vinci would call perspective painting the "soul of art." Now, if we are at all familiar with al-Haytham's *Kitab al-Manazir*, we will find that Alberti begins *De Pictura* with a direct paraphrase of it. He writes of his own observations about light and color, noting "every color when placed in shadow seems not to be the same as it is in brightness" and, therefore, "there is a close relation between colors and lights with respect to seeing" (compare these statements with quotations from al-Haytham in Chapter 7). Still more, Alberti repeatedly invokes al-Haytham's idea of the "visual pyramid," which meant a thee-dimensional field of vision expanding in size away from the eye, concluding that: "Painting . . . is nothing other than a cross-section of a visual pyramid on a certain surface." *De Pictura* makes no references to any sources except those of antiquity – we see here a new type of strategy for elevating one's own authority. Yet there can be little doubt: this key breakthrough in Renaissance art owes more than a little to one of Islam's greatest scientists.

But how did this come to help science advance in turn? The answer, in some ways, is simple but also extremely far-reaching. It returns to the powerful capabilities that Renaissance art now had to portray three-dimensional forms with convincing realism. One domain where this came to have central importance is medicine. We have mentioned the eminence that Galen's works came to have in the university curriculum, along with that of Avicenna. By the 15th and early 16th centuries, Galen's prominence in the greater medical community of Europe was supreme and unchallenged to such a degree that when a discrepancy arose between what was observed during an operation or human dissection and what Galen had said, the Galenic word would be considered correct. Since Galen had used Barbary apes for his dissections (Rome having banned using human cadavers) and anatomical descriptions, errors began to pile up. This was especially true in Italy, where university medical education had included human dissection since the 14th century. At the same time, the corpus of Galen's works (and Avicenna's too) was poor in illustrations; the visual dimension to medicine remained quite impoverished. While a few anatomical works starting in the late 1300s did include illustrations, these tended to be limited in number and simple in overall design.

This was to change dramatically in 1543, with the publication of *De humani corporis fabrica* ("The Structure of the Human Body") by the 29-year-old Andreas Vesalius (1514–1564). Working on a new edition of Galen's complete writings, Vesalius had uncovered the truth of the great doctor's use of apes as substitute humans. This had gone undiscovered for centuries. Vesalius did not dare employ the fact as a weapon but instead published his seven-volume work with no less than 273 separate plates showing human anatomy through a progressive stripping away of skin, tissue, muscle, organs, and so on down to the bones. The unmatched detail, precision, and visual realism, using every technique of Renaissance portrayal, soon established an entirely new model for medical illustration that has continued down to the present. An example, showing male musculature, is given in Figure 9.5.

Note that the figure in this image is given the pose of a classical nude, as in a Renaissance painting. The background, meanwhile, is also artistic: our eye passes over a landscape of hills, foliage, ruined castles, and a bay in the distance. By such artistry, Vesalius hoped to raise the level of his work above that of other treatises, increasing the authority of the illustration, showing the most sophisticated techniques of visualization. There is much more that can said about this image – the emotion of noble agony it carries ("I am suffering so that you may observe me"), the implication that we are thus being shown the landscape of the visually human at every level (skin, muscles, viscera, bone, spirit). Yet the core message remains the same: to learn anatomy, the student or physician must be an observing witness to the actual reality, not just a reader of books.

Vesalius, despite his magnificent achievement, did not overturn Galen in a single blow. It would require another century, and new writings that modeled their details and their illustrations on the new Vesalian standard, for this to finally happen. The 15th and 16th centuries are really the time when illustration becomes a major new part of scientific expression, a record of accurate observation and witness.

New World in the old

If the late medieval and Renaissance period expanded European abilities to portray the natural world, the so-called Age of Exploration opened up a whole new realm of demand to do so. This was no small thing. It was a primary factor in the advance toward modern science.

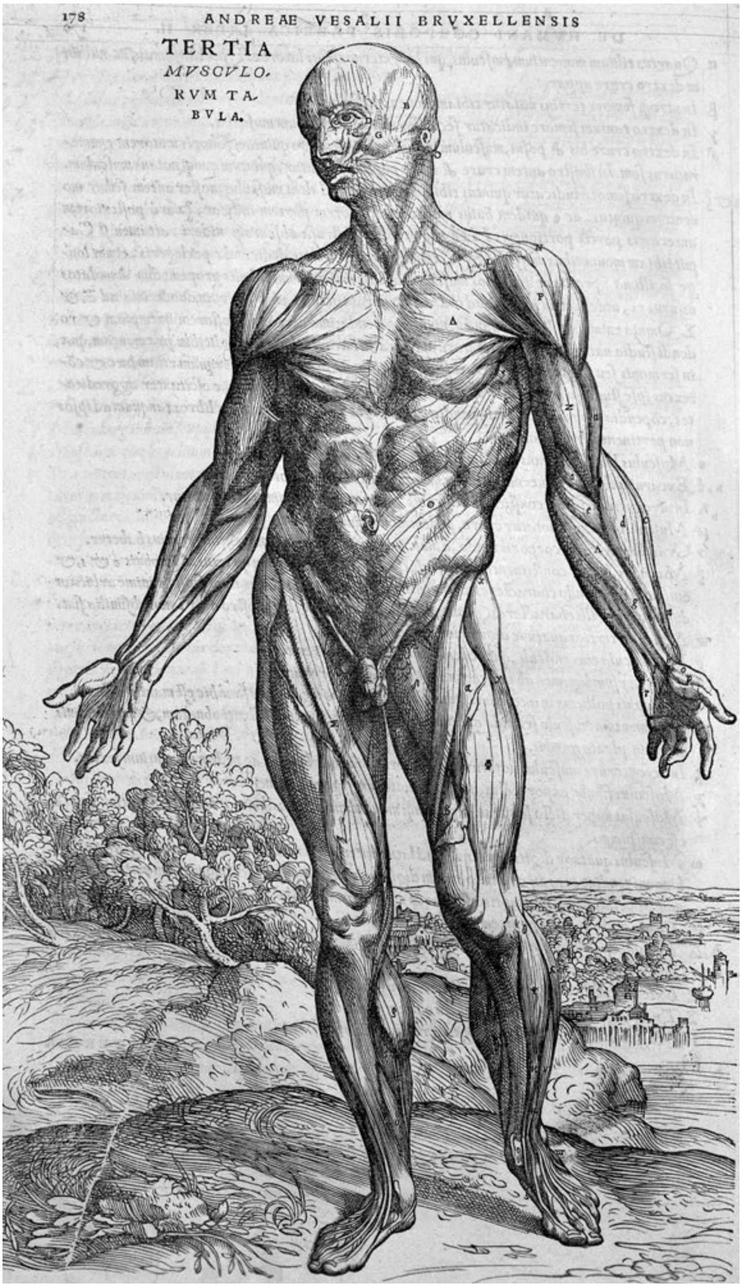


Figure 9.5 Anatomical illustration, showing male musculature, from *De humani corporis fabrica* ("The Structure of the Human Body," 1543) by Andreas Vesalius. Image shows figure in a Renaissance pose against a landscape background of hills, foliage, and castle ruins. © Wellcome Library, London

The Age of Exploration was the beginning of colonialism and thus a dark chapter in the history of many parts of the world. Colonialism links the Renaissance directly with the modern era in the incalculable devastation that it brought to human populations up through the early 20th century. Our task here is not to ignore these realities but to focus on the impacts the earlier part of this era had on European scientific culture. Whether it is fair to say that the new knowledge arising from overseas voyages in the 15th and 16th centuries are implicated in the atrocities of colonialism remains a difficult and challenging question.

What were the motives for these voyages, many of which were long, perilous, and almost certain to bring death? Trade and profit were certainly a motive. Since Genoa, Venice, and the Muslims controlled the spice trade through the Mediterranean, Portugal and Spain sought new routes around Africa and across the Atlantic. Then there was the hope of glory, for king, country, and self. Nor can we overlook the role of religion, the desire (and the church's insistence) to bring God's word to peoples everywhere. We then have three main motives. Do they cover everything?

When we read the diary of Christopher Columbus from his first voyage, for example, we find all of the above motives stated plainly and obediently in the very first entry. Columbus reviews what he has been commanded to accomplish by the Spanish crown. But then we come upon something else: "And for this purpose, I thought of writing on this whole voyage, very diligently, all that I would do and see and experience." He goes on:

> I propose to construct a new chart for navigating, on which I shall delineate all the sea and lands of the Ocean in their proper positions under their bearings; and further, I propose to prepare a book, and to put down all as it were in a picture, by latitude from the equator, and western longitude.

These are not the words of a man driven by religion, loyalty to crown, and prospect of profit. Columbus wishes also to document and preserve. His desire is to see new things, to acquire new knowledge, and to record and share such knowledge. It is also to create an image, a map in fact, with his own trace across the world inscribed in time and space. He is aware, in other words, that he will be a discoverer, not just of sights, but of facts and truths that no European has ever possessed.

Europeans, in fact, were the first humans in documented history to traverse the globe, to see the Earth in circumference. The meaning of this for science was considerable, for it meant an expansion of the heavens as well as the world. Astronomy now had to take full account of the southern skies, their stars, their view of the Moon and planets, the Milky Way, and more. A new type of feature, the Magellanic Clouds, though known to the ancient Polynesians and Maori as navigational guides, were first observed by Europeans at the end of the 15th century and acquired the term *nebucula* ("forever cloudy"), from which "nebula" is derived. All of this required the production of new celestial globes and maps. The first star atlas to include both the northern and southern skies was Johann Bayer's famous *Uranometria* ("Measure of the Universe") published in 1603, which included 12 new constellations.

Explorations of the southern seas were necessary to help defeat the paralytic authority given to Greek authors. We have spoken of this with regard to Galen. It was no less true for Aristotle and Ptolemy. Both authors, and many European commentaries and digests of their work including Sacrobosco's *De Sphaera*, stated that the Earth's equatorial regions were uninhabitable due to the excessive heat. Needless to say, this proved less than accurate. A good many of the details on Ptolemy's map of the world in his *Geographia*, a work also of enormous influence, were shown to be completely in error. Some of its more egregious errors were to combine Sri Lanka and Sumatra and to give China an east coast that bounded the Indian Ocean. Ptolemy's estimate for the Earth's circumference was about 28,800 km (18,000 mi), far below the actual number of 40,000 km (which Eratosthenes had derived), and may have helped persuade Columbus that China and India were in the place where he found Hispaniola instead.

For decades, Ptolemy's map was updated, made to look better than it deserved. But in 1570, the Flemish cartographer Abraham Ortelius (1527–1598) brought out the first true modern atlas of the world, consigning Ptolemy's version to ancient history (Figure 9.6). Ortelius named his atlas *Theatrum Orbis Terrarum*, "Theater of the World." Why "theater," we might ask? Because the author places it before us, as if upon a stage, to be seen. What does Ortelius have to say about the New World? "It is something beyond our estimation that this region called America,

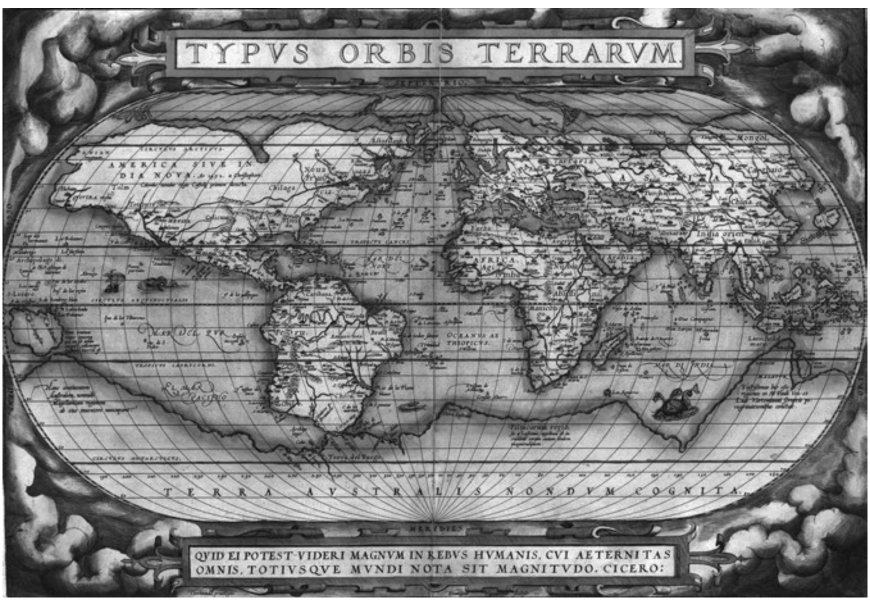


Figure 9.6 World map of Abraham Ortelius, from *Theatrum Orbis Terrarum* ("Theater of the World"), published in 1570. Renaissance maps often combined mathematics, geography, and art. The "unknown southern lands," assumed to exist, had not yet been discovered.

which occupies nearly half the world, was unknown to the ancients," and here he mentions Ptolemy, Strabo, Pliny, the major geographers of classical Greece and Rome. The world, in short, had to be reconceived. At the bottom of Figure 9.6 is a quote from Cicero: "For what human affairs can seem important to the man who keeps all eternity before his eyes and knows the vastness of the universe?" Maps, in other words, were the grand stage of the era, blending science and mathematics, art, literature, theater.

The New World, of course, was the source of much else brought back to Europe. A great mass of information, plant and animal specimens, minerals and gems, drawings about natural phenomena, as well as the gold, silver, and jewelry pillaged from native peoples. After Columbus' first voyage, the Spanish crown demanded records be kept of what was seen and found. By the late 1500s, they were sending physicians to collect and test medicines, and soon after, those knowledgeable in agronomy, mining, and natural philosophy. This approach became a model taken up and expanded by other exploratory efforts, for example those funded by Sir Walter Raleigh along the eastern coast of North America. In every case, Europeans acquired critical knowledge from the local peoples, for instance the process to make quinine medicine or to produce rubber.

The new voyages, then, were epochal for Europe's own scientific culture and for the history of science as a whole. They could not have happened, however, without major advances in shipbuilding and navigation. Indeed, to the degree that they depended on such advances, they also stimulated them. By the mid-16th century, an ocean-going European ship was outfitted with a formidable array of technologies that gave it unprecedented capabilities: a mixture of rectangular and triangular (lateen) sails, enabling it to tack into the wind and maneuver in any direction; a moveable rudder attached to the stern, aiding such maneuverability; enormous fire power in the form of onboard cannons; an advanced dry mariner's compass (its needle floating in air, not water); and improved astronomical instruments, including the mariner's astrolabe, cross-staff, and quadrant. It is no exaggeration to say that, with this panoply of equipment, the typical ocean-going vessel from Europe was the product of a scientific culture rapidly surpassing all others.

This being said, where did all this technology originate? Nearly every item mentioned either came from, or was directly influenced by, innovations in Islam and China. The cross staff, an instrument for taking altitudes of celestial bodies (including the Sun) and thus determining latitude, was based on the *kamal* of Muslim mariners. The astrolabe, invented in Hellenistic Greece (often attributed to Hipparchus), was further developed into a sophisticated instrument during Islam's "golden age." We have seen, meantime, that the compass and cannon were invented in China and transmitted to the West, but so was the idea of the stern-mounted rudder. As for the lateen (triangular) sail, this was first developed in Roman times, probably in the eastern Mediterranean (details not known), and was later made a standard first on Byzantine ships and then Muslim vessels in the Mediterranean Sea, Persian Gulf, and Indian Ocean. It was adopted by the Portuguese under Henry the Navigator (1394–1460) to create the ship known as the caravel, a fast and highly maneuverable vessel that extended European seafaring down the West African coast and out into the North Atlantic.

Europe's Age of Discovery, therefore, was made possible by technology from other parts of the world. We could even say, with no little justice, that the powerful new vessels enabling this era were, in fact, containers bursting with inventions and ideas from nations as close as Greece and as distant as Persia and China.

Paper, printing, and science

The impact of print, using moveable type, was as profound on science as on any domain of expression. It made books abundant, easy to replace, simple to distribute, affordable to far more people than manuscripts, and of guaranteed reproducibility. It enhanced scientific communication, expanded its visual elements from images such as those of Vesalius to mathematical symbols and complex geometric diagrams. Just as important was its effect in accelerating such communication – printing a pamphlet, treatise, or long book could be done far more quickly than if it were copied by hand. By allowing scientists to exchange ideas and information more rapidly, with assured accuracy (no more relying on scribes who might make errors), printing acted to accelerate science itself, even as it expanded its reach. Moreover, print increased the fame of those working in the sciences. Their work, that is, could be broadcast to an ever-greater number of readers, both within the scholarly community and universities and without. The advent of print helped to grow literacy throughout Europe, thus the intellectual market for new ideas and knowledge.

The print revolution (as it is often called) also arrived at an excellent historical time. The vast amounts of new information from overseas exploration and the surge in demand for maps, charts, manuals, and other aids to navigation and documentation were certainly important factors. So was the growth in the number of universities and, still more, the size of their student body: by 1500, nearly half a million students had been matriculated since the 14th century, with numbers having tripled in some countries (Italy, Germany) since 1400. Among the wealthy and the new middle classes, there was growing demand for books on the new overseas discoveries, not least those having to do with nature.

We can also point to the advances in art and illustration as reason for why print aided science. More finely detailed woodcuts and the advent of etching in the late 16th century were able to wonderfully enhance the use of Renaissance techniques in three-dimensional imagery. If Vesalius provides one famous example of this, another comes from the work of none other than Galileo: in his hugely influential little book *Sidereus nuncius* ("The Starry Messenger," 1610), he documented his telescopic observations of the Moon (among the very first) in four etchings that persuasively showed it to be, not a pure crystalline sphere as generally supposed (and as claimed by Aristotle), but instead a complex and rocky world like the Earth itself, full of high mountains, protruding ridges, and deep valleys.

Printing was thus of enormous importance, yet it too depended for its impacts on another invention. Before papermaking was introduced in the early 12th century, the preferred medium for writing was parchment – the dried skin of an animal, usually a sheep, but goats and calves were also used (vellum is the specific name used for calf skin prepared for use as a writing medium). It was a true craft and could not be done on an industrial scale without a large number of workers. Making parchment involved cleaning the skin of any flesh and hair, stretching it out on a wooden frame, then scraping it with a special knife to create a regular, smooth surface, and finally wetting and drying it several times while stretching it further to reach the right thinness before cutting it into sheets. Depending on the purpose for which it was intended, the resulting parchment might be further scraped with pumice and rubbed with chalk, to ensure the best possible absorption of ink. The process was thus labor intensive, making the result expensive. It was not cheap from the sheep's point of view either, as no fewer than 300 had to supply their skins in order to make a single Bible.

Paper was first established in northern Spain. Unlike printing, it did not spread rapidly and decisively until innovations were made, particularly in the cities of Amalfi and Fabriano. In these places, by the early 1300s, water power and a stamping mill (to produce pulp), along with a wire-mesh mold (for forming sheets) and a rapid-feed paper press (for squeezing out water and thus accelerating the drying process) had been introduced. This made papermaking an industrial process. Costs fell, and the technology began to spread.

With the print revolution, demand for paper veritably exploded. By the time Columbus sailed on his first voyage in 1492, there were paper mills throughout Europe. Only eight years later, in 1500, it is estimated that as many as six *million* books were in print, testifying to the immense changes underway.

One of the printers who contributed significantly to such numbers was located in Venice. Aldus Manutius, already highly successful, was one day contemplating the future of the business when he had a groundbreaking insight: the largest market for books, which would surely grow in coming years, was not interested in religious works, especially expensive editions of the Bible, but instead in smaller, cheaper, secular books like vernacular translations of famous Greek and Roman authors. Thus, in a sense, was born the concept of the "everyman" edition, later the cheap paperback of a great classic. In the case of Greek authors, this included scientific thinkers and philosophers – Aristotle, Hippocrates, Galen, Strabo – as well as dramatists, poets, and historians, such as Sophocles, Pindar, and Thucydides.

Manutius advanced the book world in a way that helped produce a true reading public (though a small one, to be sure, judging by percentage of total population). His Aldine Press was the very first to issue print runs in the thousands. Thus, even before the time that Francis Bacon had begun work on the *Novum Organon* and Galileo had trained his telescope on the Moon and Jupiter, the production of paper and books had become a large-scale capitalistic enterprise.

New cultures of technology and European innovation

If we can say that Europe had a Scientific Revolution of some kind, whether lasting 100 or 400 years, we can say the same of technology. Changes began as early as the 9th century but then gained force and momentum into the 1100s and beyond. All in all, as historian George Ovitt has written, "it took the remarkable infusions of Asian – Chinese, Indian, and Islamic – inventions to stimulate Western inventiveness and the economy of Europe."

Some of these inventions we have already mentioned. Paper, the compass, and gunpowder are among those that came from China. There were others: the cam (11th century), wheelbarrow (12th century), and cast iron (13th century). The cam and camshaft, by which circular motion (e.g. from a waterwheel) is translated into linear motion (hammers), was especially important to the great expansion in water power that took place between the 11th and 13th centuries, when new levels of mechanization were achieved. This included the driving of bellows in industries such as brewing, glass-making, and iron forging, as well as the grinding of grain and the fulling of cloth. Another important power technology was the windmill, first invented for practical use in Persia around the 9th century. European windmills did not appear until the late 1100s and had quite different designs, being vertical, with large, sail-like blades, in contrast to the Persian examples, which had small, horizontal blades. This has led most historians to suppose they were invented independently, though some scholars suggest the idea for such a machine came to Europe from Central Asia, where windmills were also abundant.

Architecturally, Europe benefited greatly from the pointed arch, known today as the "gothic arch." This elegant form allowed the great majority of overlying weight to be transferred directly onto supporting columns instead of the arch itself, thereby allowing for very tall structures. This arch became the fundamental design feature of the magnificent gothic cathedrals, with their soaring, vaulted ceilings and high-arched galleys and nave. While the detailed history of this feature remains debated, it is agreed that Europe borrowed it from Islam, specifically Persia, which had adopted it in turn from India sometime in the 9th century.

Yet another surge in technology was related to cotton. This fiber, well-known to Indian, Chinese, and Muslim civilization, wasn't introduced to Europe until the 12th and 13th centuries, when areas in Spain and Sicily that had cotton industries run by the Muslims were taken over. Also adopted was the *churka*, a device consisting of two rollers and a crank that squeezed the raw cotton through and forced out the seeds, thus leaving only the fibers. First developed in India centuries earlier, this early type of "cotton gin" would remain in use down to the late 18th century. Europeans, however, advanced it using foot pedals, gears, and even flywheels.

It is important for us to dwell on the meaning of this word, "advanced." As we have seen with other scientific cultures, to simply say that a technology or area of knowledge was "borrowed" or "imported" and then "adapted" or "improved" is never enough. Why were certain technologies selected for adoption and not others? Who adopted them? In what way or ways were they adopted? Why and how were they advanced? Every technology or piece of knowledge has an instructive story.

Take the compass, for example. We have described its origins in China (Chapter 6), where it was used for maritime navigation starting in the Song Dynasty, probably in the 11th century. First reference to it in a text dates from 1111–1117 and indicates use of a maritime compass was already common practice. The technology employed a magnetized iron needle floating in water. A "dry" version existed, with the needle suspended, e.g. by a silk thread, but sailors continued to prefer the "wet" technology for reasons that are not clear.

As to when it came into European hands, the story is a bit fuzzy at first. First report of it was in writings by the English scholar Alexander Neckam (1157–1217), dated around 1190 in his treatise *De utensilibus* ("On Instruments"). This was followed in fairly short order by a number of other mentions over the next 50 years in books of poetry, history, and natural history. It isn't evident whether a "wet" or "dry" version was in use by navigators, since both are mentioned only once each and a majority of references don't mention either.

But in 1269, a new and more advanced stage in the history of the compass began. In this year, a French scholar-engineer, Pierre de Maricourt, also known as Petrus Peregrinus (Peter the Pilgrim), performed a series of high quality experiments on pieces of lodestone. Precious little is known of this man's life; perhaps the longest treatment of him comes from no lesser a thinker than Roger Bacon, who may have been his pupil or friend (or both). In his work *Opus Tertium* (ca. 1267), Bacon calls Peregrinus "a master of experiment" and says "he knows all natural science whether pertaining to medicine and alchemy, or to matters celestial and terrestrial. He has worked diligently in the smelting of ores as also in the working of minerals . . . besides which he is skilled in agriculture and in the measurement of lands." As if to merit Bacon's admiring comments, Peregrinus wrote up the results of his experiments in a brief little treatise called *Epistola de magnete* ("Letter on the Magnet"), setting a new level of knowledge about the magnet, while also proposing a sophisticated "dry" compass for use both on land and sea.

The *Epistola de magnete* is a fascinating little book. Less than 40 pages in length, it offers a window into the scientific mind that Europe had begun to make possible. Taking its cue from Muslim and Greek thinkers, it is divided into two parts, the first dealing with the findings and "theory" about the nature of the lodestone, the second applying this information to the design of a new instrument. In Part 1, the author makes explicit some important properties of magnets, such as the existence of two ends that can attract or repel each other (the Chinese undoubtedly knew this as well, but there is no record of such understanding being communicated to Europe). Peregrinus seems the first to use the term "poles" for these and to label them "north" and "south." His experiments involved breaking a stone into fragments and testing them, discovering that that every piece was a complete magnet on its own. He states that the lodestone "bears in itself the likeness of the heavens . . . ," specifically having two points, "one the arctic or north pole, the other the Antarctic or south pole." This may well be the first time a direct connection is made between the Earth's poles and those of a magnet – in truth, the author is referring to "the celestial sphere," not the Earth specifically. Yet the link between poles of a magnet and those of the Earth remained influential and was later used by William Gilbert in his enormously influential *De magnete* published in 1600, the first work that finally pose the Earth itself as a great magnet.

Based on his findings in Part 1, the author tells us how to build a circular compass. These directions include making a ruled circle, with 360 intervals, that highlights the four cardinal directions (Figure 9.7). For the "dry" compass, he says to

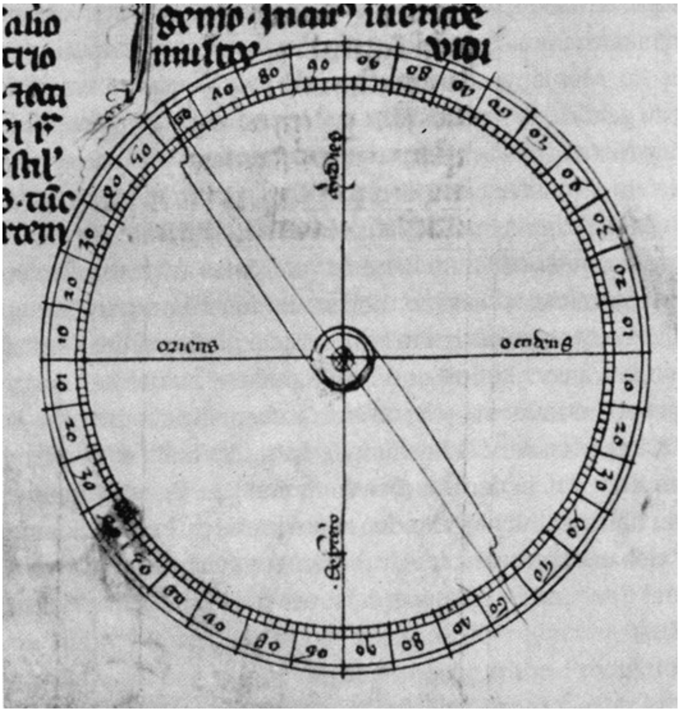


Figure 9.7 Drawing of compass face from a 16th-century print edition of Petrus Peregrinus' *Epistola de magnete* (originally published in 1269).

place in a wooden container, with a transparent cover to it, a thin axis made of brass or silver – that is, a non-magnetic material – extending from the bottom of the container to the top cover and able to turn freely. An iron needle is then inserted into a hole through this axis and magnetized with a lodestone. Thus the needle is suspended in mid-air and will turn on the axis. "By means of this instrument," says Peregrinus, "you can direct your course towards cities and islands and any other place wherever you may wish to go by land or sea, provided the latitude and longitude of the places are known to you." As we know today, this was no boast.

By the early 14th century, the "dry" compass was in regular use by Italian merchant ships on the Mediterranean. While we don't know how much influence *Epistola de magnete* had on maritime compasses, it was certainly a widely known and much read text. It exists today in 39 manuscript copies, a large number indicative of its popularity.

Peter Peregrinus' small book shows that by the mid-to-late 13th century, a wholly new approach to understanding nature had begun to take hold in Europe. The *Epistola* is an entirely secular work; nowhere is God present in its pages, whether as agent, judge, or creator. This is true even though there is repeated mention of the heavens and their powers, human frailty, the nature of materials, and other subjects that in earlier texts would occasion a phrase about divine ways and means ("Benefiting from God's favor, I discovered that . . . ").

Within the covers of this little volume is, therefore, a new world. Indeed, it is a world inspired by, but reaching beyond, the scientific cultures of Islam and the Greeks. It is a world of physical realities that can be probed, discovered, understood, and utilized by human beings without any divine guidance or meaning. It is a realm where the study of texts, especially older texts, is not the substance of the effort. Still more, as shown by the author's attempt to harness cosmic "virtue" for perpetual motion, it is a world whose limits are not well defined and, therefore, are available for testing, even manipulation. Unlike Muslim, Greek, Hindu, or Chinese thinkers on the heavens, Peregrinus wants to go further than to simply understand and predict celestial phenomena; he wants to make use of their forces, pull them down to Earth in a sense. His book, with its direct, unadorned style of writing, its organization of "discovery first, then application," its use of diagrams, and its ambition to add to the stock of available knowledge, is itself a pointer in the direction of the future, to what science will one day become.

A plague for science!

The 14th century was not the best of times in Europe. The Black Death, which raged from 1343 to 1351, peaking between 1347 and 1350, killed somewhere in the range of 35–50% of Europe's people. It left many villages, towns, and sections of cities without a single living person. In many urban centers, where the disease did its worst work, more than half the population died; Florence lost two-thirds of its people. The plague brought low every major activity, from agriculture to jewelry making, and it killed off many good minds as well. The tales of horrors, told by witnesses like the great author Boccaccio, are enough to make us shudder even today.

Yet, historians now believe the set of diseases comprising the "great pestilence," as it was then called, had benefits, not least for science. Some of these stem from the interpretation that the Black Death was a pivotal event of change in European history. On the one hand, it hastened the collapse of feudalism, thereby aiding the rise of a mercantile class over the next century-and-a-half and thus a long-term background for new technology and also the "Age of Exploration" itself (which never would have happened under feudal society).

But an equally positive impact was felt by medicine. This might seem ironic. Didn't physicians, like priests, fail entirely to alleviate the suffering and stem its terrible spread? Yes, and this is exactly the point. Existing medical training was seen to be wholly inadequate and had to change. But *what* needed to change, exactly? The highest level of medical training, that in the universities, responded to the situation by following Galen: seek to define the cause(s) and proceed from there to prevention. In this case, the causes were identified in astrology – a conjunction of Mars, Jupiter, and Saturn in the constellation Aquarius caused the Earth to exude "corrupting vapors" poisoning the air. Prevention, then, meant avoiding corrupted atmosphere, i.e. swampy and moist areas, winds blowing from the south, "agitated air," and so on. Missing was any interest in the sick themselves, practical methods for treating them.

This did not last. In the decades following the Black Death, actual manuals of clinical medicine, both for physicians and for surgeons, began to appear. New kinds of texts, on anatomy for example, were also published, reflecting a priority given to hands-on observation. By the early 15th century, these manuals and treatises had become standard in the medical profession. Human dissection became more common, and, though primacy was still given to Galen's descriptions, discrepancies with what was actually seen in human cadavers began to be noted, forecasting the eventual necessity to substitute empirical reality for ancient authority.

The new emphasis on intervention during an illness also supported a view of contagion emphasizing the possibility that the sick were themselves primary carriers. Such was not an idea strongly supported by the theory of humors. Yet, on the basis of observed patterns, isolating the sick was increasingly interpreted as a viable practice. In the late 14th century, the port town of Ragusa (current-day Dubrovnik) on the Dalmatian coast decided to make arriving ships wait for 30 days before unloading and letting sailors come ashore. This was later expanded to a 40-day period (for reasons unknown) that, in Italian, was called *quarantine*. Thus the origin of our word "quarantine."

Roger Bacon and his task

Born just after the turn of the 13th century, in Somerset, England, Roger Bacon (1214–1294) presents us with a transitional mind bridging in some ways the era of translation and that of a new scientific culture. After studying at Oxford, he became a master there, then taught at the University of Paris from about 1240. He seems to have been an outspoken critic of things and people he did not like. While at Paris, he led a campaign promoting a change in the *quadrivium* toward study of the "new sciences" and mathematics. He had already turned his mind away from traditional subjects, such as theology, toward these newer disciplines, which he intended to pursue until he fully mastered them.

Bacon did not always favor the Greeks over Islamic authors in this effort. He certainly did not see the latter as damaging an original wisdom but as often improving it or going beyond it. Bacon himself was a polymath, as were several other influential thinkers of the 13th century, notably Albertus Magnus (whom Bacon did not care for) and Robert Grosseteste (whom he admired greatly). Few authors of his century, however, so fully assimilated Greek and Islamic thought, especially about optics, which, as we have seen, also meant astronomy, mathematics, and even art.

Bacon has often been credited with his support for experimental science. Modern historians have sometimes seen him as a proto-modernist and champion of laboratory methods. More recently, however, he has been put back among medieval thinkers. This is because Bacon's chief source for his scientific writings is not empirical study of nature directly but instead other books, what other authorities have said. Nonetheless, it remains true that, like al-Haytham, he is a proponent of testing ideas and confirming observed patterns. It is an error to try and make of him a modern thinker but it is no less mistaken to confuse him with those who lived in earlier centuries.

So, then, what does Bacon actually say about experimentation and its value? In his section on "Experimental Science" in the *Opus Majus,* he begins by stating "without experience nothing can be sufficiently known":

> For there are two modes of acquiring knowledge, namely, by reasoning and experience. Reasoning draws a conclusion and makes us grant the conclusion, but does not make [it] certain, nor does it remove doubt . . . unless the mind discovers it by the path of experience. . . . For if a man who has never seen fire should prove by adequate reasoning that fire burns and injures . . . his mind would not be satisfied thereby . . . until he placed his hand or some combustible substance in the fire. . . . But when he has had actual experience of combustion his mind is made certain and rests in the full light of truth. Therefore reasoning does not suffice, but experience does.

Bacon next takes Aristotle gently to task for saying that "proof is reasoning that causes us to know"; a "proviso" is needed, Bacon says, that the proof – which, of course, is no proof at all – must be "accompanied by its appropriate experience." He does not come out and say Aristotle is wrong. Indeed, he quotes from him far too often to do this. Such is the historical problem he finds himself in, we might say. Still, he sums up his points in straightforward fashion: "He therefore who wishes to rejoice without doubt in regard to the truths underlying phenomena must know how to devote himself to experiment."

There is a story about an experience Bacon had with his students at the University of Paris. At one point during a lecture on Muslim philosophy, he used a term that he referred to as Arabic but which some of his students informed him, while laughing, that was actually a common Spanish word. Deeply embarrassed by the episode, Bacon realized there was much to be gained from the study of languages. He then began his own program to learn the four tongues he thought most needed in studying philosophy: Greek, Hebrew, Chaldean, and Arabic (not Spanish).

Bacon is also credited with being the first European to describe the explosion of gunpowder and to report on its ingredients. In the *Opus Majus*, he writes:

> We have an example of these things in that children's toy, which is made in many [diverse] parts of the world, a device no bigger than one's thumb. From

> the violence of that salt called saltpeter [together with sulfur and willow charcoal] so horrible a sound is made by the bursting of a thing so small, [held by] no more than a bit of parchment, that we find [a noise] exceeding the roar of strong thunder, and a flash brighter than the most brilliant lightning.

We can guess that Friar Bacon, at some point, was witness to a Chinese firecracker going off. It is not true that he published, somewhere, an actual formula for combining the three components.

In the centuries after his death, Bacon was turned into an alchemist and wizard of extraordinary powers, capable of creating mirrors that could light a candle at night and show what certain persons were doing anywhere in the world. Fantastic tales were spun about him – he was said to have created a "brazen head," a great bronze bust able to answer any question put to it – as if he had been in possession of nature's most formidable secrets.

Even in this, Roger Bacon offers a link to the present. His reputation, that is, turned him into a kind of sorcerer, a man who had so much knowledge of hidden powers that he himself was touched with the supernatural. Such beings, of course, were part of the lore of many cultures. In Europe, it also found a specific legend in the story of Faust, who sold his soul to the devil for knowledge and youth. Bacon was never treated as a version of Faust but could be viewed as a forerunner. What of the modern era? We have a gentler version, perhaps. Albert Einstein, scientific genius beyond all others, who unlocked the universe with a tiny equation, shaped like a key, showing that the two most opposite realities – solid matter and invisible energy – were in fact one and the same.

Concluding comments

In this chapter, we have examined bits and pieces of history spanning the period between the 1100s and 1500s. These fragments, however, we have seen to be connected in various ways. They show links among the sciences, the arts, and theology as well. The new knowledge from Islam, with its own legacy drawn from India, Greece, and China, found a particularly welcoming home in late medieval and Renaissance Europe. Results and advances that came from this knowledge later on had to face some resistance from the Catholic Church, it is true, especially about the heliocentric view. But by then it was too late. The church had no final control over Europe's scientific culture, which was rapidly moving beyond ancient ideas in a host of areas besides astronomy.

Europe was not a peaceful place between the 12th and 16th centuries. The Crusades began in 1096 and continued for 200 years, while the Reconquista in Spain lasted into the late 1400s. The Hundred Years' War between England and France continued from 1337 right through the Black Death to 1453. There were many peasant uprisings, local civil wars, conflicts over royal succession, repeated battles against the Mongols and the Ottomans, religious struggles culminating in the Reformation. Yet, despite all of this, the greater part of Europe was never invaded by a foreign power. It never suffered the destruction of its most sophisticated cities, the loss of its universities and libraries, the widespread execution of its scholars. Nor was its intellectual culture ever centralized or standardized. Limited though it certainly was, the opportunity for individual thinkers to find space for original work, writing, and also community with others of their kind were still greater than anywhere else.

From what we have seen, we can appreciate that Europe benefited from several factors when it came to scientific advance. Europeans imported the greater part of the most advanced science and technology humanity had to offer. This meant the world of knowledge from Islam, Persia, India, China, as well as ancient Greece. Such material arrived, moreover, at a particularly auspicious time. By the late 11th century, Europe had launched a major expansion in intellectual life, mobility, international contact, trade and commerce, and more. It was, therefore, ready and able to make excellent use of the new knowledge when it came. In fact, it underwent two such episodes of intellectual vitalization, the second, as we have discussed, being the Age of Exploration and all that it came to mean for scientific thought and study.

Let us give one final example to show the truth of all this. Eyeglasses were invented in Italy (Pisa or Venice) about 1285. While the inventor remains unknown, it is universally understood that Alhazen's (al-Haytham's) *De aspectibus* and possibly a lost work on mirrors and lenses were a necessary influence behind this invention, due to their detailed discussion of how images can be enlarged by convex lenses. Alhazen's writings were taught in a number of universities and had been written about by famous Latin scholars, as we've noted. By the middle of the 15th century, magnifying lenses and glasses were common items in daily life, cheap enough and reliable enough to have become available to most people in society, including scholars and their students. We can hardly doubt, in other words, that these visual aids brought a positive impact on scholarship itself, including all the sciences, since it allowed a good many minds to remain productive in reading and writing decades longer than in previous centuries.

The story does not end here, however. Lens makers who supplied glasses were the ones who pursued other, crucial inventions. Both the microscope and telescope emerged from such artisans in the Netherlands during the late 1500s. The original motive behind developing the telescope, in fact, seems most likely its usefulness to navigators, sea captains, and other explorers. The market for a new eye on the world, so to speak, was very large by this time. Yet the telescope proved to be an invention that scientists themselves, like Galileo, could build and improve and find new uses for by looking higher in the skies.

Today, of course, these two instruments are still very much at the core of observation in scientific endeavor. They have proliferated into a great number of forms: while the most advanced telescopes are now able to orbit the Earth and have opened a whole new era of visual discovery regarding the heavens, their correlatives on Earth in the realm of the microscope have been able to do nothing less than give us images of atoms (Figure 9.8). From this, it is no leap to the vision charted by the mathematician and philosopher Blaise Pascal (1623–1662), who wrote that the

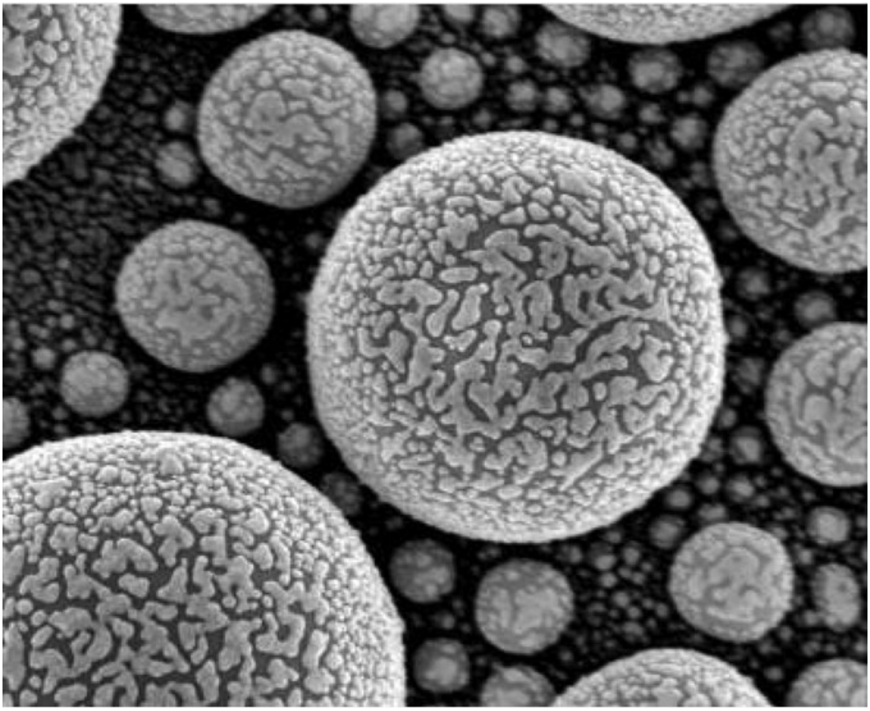


Figure 9.8 An image of gold atoms on a base of tin, produced by a scanning electron microscope. Source: National Institute of Standards and Technology, U.S. Department of Commerce.

human mind forever strives between the realms of the infinitely small and the infinitely large. In this, we can perceive a silver braid that links these powers of today to the past. Such powers, that is, are only the latest manifestation of an intellectual line linking Newton, Kepler, Bacon, al-Haytham, al-Kindi, Ptolemy, Euclid, and undoubtedly earlier names from Egypt, Mesopotamia, and India as well.

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10 Conclusion

Themes in the world history of scientific cultures

> Histories make men wise; poets, witty; the mathematics, subtle; natural philosophy, deep; moral, grave; logic and rhetoric, able to contend.
>
> Francis Bacon, *Essays*

The history of science is the history of civilization. Or, to put this another way: the history of scientific cultures is the history of world civilizations.

Every people or group of peoples who succeeded in building a major civilization, from ancient Sumer to Renaissance Europe, did so by advancements in science and technology. Not by science and technology alone, of course. Other elements were also necessary: political and legal institutions, a strong economy, religious coherence, social mores, literary and artistic traditions. Yet, even with these other elements in place, civilizations have stagnated, weakened, and eventually failed without continued evolution in scientific culture. This is because such culture impacts the physical dimensions of life at every conceivable level, from food and health to the measurement of time. No less, it contributes to the ways in which a civilization comprehends the order of the world and its place in that order.

Such comments draw us toward other comparisons and conclusions. Perhaps the best way to pursue these is to look at some of the principal themes that we've identified in the preceding chapters and to briefly chart their role. These are themes that have risen to the surface again and again, in ways that are both fascinating and suggestive. Choosing the most interesting among them will allow us only a few comments on each but will help us make sense of some larger patterns. Furthermore, it will highlight how truly interdisciplinary the history of science has become, as a means of probing and revealing central aspects of civilization.

Theme 1: influence

Each of the scientific cultures we have examined was different, unique, and uniquely inventive in certain ways. And yet none was isolated, untouched. There were no islands of science. Major civilizations were never wholly self-created but depended for their dynamism and growth on scientific and technological influences from other peoples.

We have seen that the agents of such influence are extremely diverse. Merchants, migrants, craftsmen, soldiers, prisoners of war, teachers, translators, and wandering scholars have all played this role. Recall Leonardo of Pisa: a teen accompanying his father to a trade post in Algeria, he found reason to author a mathematics text mainly for merchants that determined how the modern world writes its numbers.

Forms of contact have also included the import of books, medicines, flora, fauna, machines, and ideas. Lest we forget, the fortunes of war have been a source of impact, for instance through the capture of engineers, technologies, texts, and territories (even entire societies). Civilizations, that is, do not just rub up against one another as if sheathed in bark. They are more like languages that penetrate each other with new vocabulary, syntax, and even grammar.

All of which highlights a conclusion. Over time, those scientific cultures that made the most progress were those that remained open to new influences from outside. Patterns here have been hugely variable, to be sure. But what appears to approach a general rule, across time and setting, is that civilizations require intellectual nourishment, and this applies to science and technology perhaps most of all. It is a rule with more than a little relevance to the world today.

Theme 2: translation as a historical force

Translation has been a major force in the history of science, from a very early time. In two cases, early Islam and medieval Europe, it rose to become a social movement, lasting centuries, creating new scientific cultures.

Yet the phenomena of translating scientific knowledge has also occurred more gradually, intermittently. Early on, transfer involved a strong oral dimension, as it must have among Egypt, Sumer, and the Indus Valley. Multilingual individuals, immigrants, or merchants were key mobilizers and remained key actors in the history of science after writing became common.

Translation, however, is not only a process of transfer. We may assume that the works of Aristotle or al-Haytham entered into different scientific cultures as a fixed and final corpus, but this is wrong. "Aristotle" in 9th century Greek is different from "Aristotle" in 10th century Arabic and 12th century Latin. These different versions show that important changes were common: new titles, new organization, rewriting or deletion of difficult passages, addition of diagrams, improved phrasing, and more.

Translation created new texts, new "originals" in each language. And in a great many cases, these new "originals" are the oldest that we have. This is true not only for Greek thinkers, but for Muslim, Hindu, and Persian authors as well. What does it say that the oldest manuscript of an al-Khwarizmi book on computing with Indian numerals, which may include passages translated from Sanskrit, is in 13th century Latin? It says that in the history of science, no less than in literature, it has been new "originals" which have had the most influence.

Theme 3: historical continuity in science

To the greatest minds of the Scientific Revolution, the past was not a foreign land. Francis Bacon, among others, may have proclaimed that a complete break from the "ancients" was urgently needed; yet in real terms, scientists moved in new directions while pursuing inspiration from ancient thought. The past was never wholly abandoned. Its soils proved too rich.

Let us consider, though, a final example. It is not widely known that Isaac Newton wrote nearly a million words on alchemy. These were not words of criticism. For more than 30 years, Newton kept notebooks on his study of alchemical texts, on his meditations about transmutation, and on his own alchemical experiments. It is not possible to separate the author of the *Mathematical Principles of Natural Philosophy*, a work many have called the greatest single book in the history of science, from a man who spent most of his adult life seeking the Philosopher's Stone.

The truth is that Newton the alchemist seems to have been essential for Newton the physicist. Historians point to his idea of an unseen, attractive force – gravity – and how unorthodox it was to mechanical philosophy in the late 17th century. A mysterious, invisible power working at a distance called upon belief in magic and the supernatural, since all physical action was thought to require material impacts, even of tiny particles. Alchemy, however, spoke of "active principles" that behaved similarly to a Newtonian force. Sir Isaac's notebooks show he was persuaded there was a fundamental principle in all of nature, the same physical principle wielded by God to shape the world. Newton's goal, therefore, was much larger than finding mathematical ways to explain the universe. In the words of historian Betty Jo Dobbs, "Newton wished to penetrate to the divine . . . beyond the veil of nature. . . . His goal was the knowledge of God."

This may disturb our image of Isaac Newton today. He was not, after all, the modern scientist we thought he was. But as we recall, the alchemical imagination wished for power over nature and life itself. In the wrong hands, this could do monstrous damage, thus there was a need for secrecy and occult language. In the right hands, however, it could bring a heavenly kingdom to Earth. In the end, modern science did not soar free from the past like some phoenix taking wing from the ashes. It was born from the ancient and the new together, from continuity as much as from "revolution."

Theme 4: science and religion

The idea that an eternal struggle exists between science and religion dates from the modern period and is fiction. It is no more accurate than the opposite, that scientists and theologians were always the best of friends.

Generally speaking, the further back in time we go, the more religious conceptions are inseparable from cosmology, astronomy, views of the Earth, and more. Yet the degree to which this was true is highly variable. As in pre-modern times, moreover, the cosmos beyond Earth is today the true realm of the infinite, of advanced forms of mathematics, and of ideas about universal creation itself.

Yet the place of religion never prevented a scientific culture's practical, inventive side with regard to minerals, ores, medicinal plants, tools, irrigation, and so on. Notions of the sacred, in fact, surely helped guide some of these developments, too. They did not dictate properties of the physical world that had to be learned and utilized.

With time, relations between science and religion became increasingly complex and diverse. In Greece, ideas dealing with divinity and morality permeate astronomical theory, as in the perfection of the circle, yet much secular thought existed alongside this, as in Aristotle or Archimedes. Muslim thinkers in their lives and works varied from the highly devout al-Kindi to rejections of Qu'ranic guidance by al-Razi. Historians also tell us to avoid thinking that forward-looking natural philosophers in pre-modern Europe rejected the church's authority or that opposition to Copernicus revealed a denial of science by Roman Catholicism. At no time were scientific thinkers all on one side of a barbed fence, theologians on the other. Perhaps the only generalization we might venture here is that the history of religion and the history of science cannot be separated.

Theme 5: the idea of order

We have also seen that the idea of order in the universe, guiding everything within it, has been shared by all early civilizations. This should neither surprise us nor send us into ecstasies about "human nature" (however defined). Order is a form of meaning and a way to give structure to existence. What seems striking is that in nearly all the scientific cultures we have examined, the source of such order has been mathematics.

There are major differences, to be sure. In Egypt of the Old Kingdom, the source was in record keeping. In Vedic India, it was the universe as manifestation of numbers. For early China, too, numbers were central but in specific patterns that both expressed and evoked invisible forces. To the Maya, the world began by being measured out, like a fertile field, four sides and four corners. With the Greeks, there was the Platonic vision of geometry, above all the circle, as the perfect structure of the universe. Geometric and mathematical stability was adopted by those civilizations that adopted Greek and Hindu science, including early Islam and then medieval and Renaissance Europe.

Such ideas of mathematics as the key to universal order were thus shared by every major civilization. This, too, is a fundamental concept that remains fully alive in contemporary science.

Theme 6: the library – a great and tragic institution

Great libraries have been fountains to which thinkers in study of nature have gone to drink. Such collections have drawn the most learned and ambitious minds in scientific cultures throughout the globe. And so they do today, though in new ways.

Some of the great collections we have encountered: the Library of Ashurbanipal at Nineveh; at Alexandria in the Egyptian city of that name; the academy of

Jundishapur in Persia (Iran); early universities in India, above all Nalanda; those of Islam, including the *bayt-al-hikma* (House of Wisdom) and the libraries of cities from Balkh to Baghdad and Cairo to Cordoba; finally, we must also include collections of Maya manuscripts that must have existed during the peak of that civilization around 700 C.E.

Europe, then, had to learn from the rest of the world the value of gathering large numbers of books. Nothing on the scale of Islam or India, for example, existed in European lands until the 19th century (in 1700, the largest libraries in Europe held less than 75,000 volumes, compared to more than 400,000 in 11th c. Cordoba).

At the same time, though so often built by emperors and kings, great libraries were themselves the casualties of empire-building. The burning of books and killing of scholars, from Nineveh to Qin Dynasty China, from the Mongols at Baghdad to the Spanish in Yucatan, has meant incalculable losses. Such is a theme that has pursued the world into the present.

Theme 7: crossroads and travelers

Because knowledge is a mobile form of culture, areas where different peoples have made long-term contact became especially fruitful for science. We have seen this in specific examples, such as the Greek city-states of Asia Minor (Turkey) in contact with Mesopotamia and areas east, perhaps as far as India. It is from this coastal district that the largest number of great scientific minds originated in ancient Greece. Another example was central Persia, which had commerce for many centuries with the eastern Mediterranean (Greece, Rome, Byzantium), Mesopotamia, and India. No other region in all of Islam provided so many distinguished thinkers in the sciences. We could speak, as well, of Spain and Italy, which became essential conduits for knowledge from the East to flow into the West. Crossroads of culture have been especially fertile for science.

There is another factor to consider. When we scan the lives of great scientific thinkers from the pre-modern past, it emerges that very few of them remained in one place. Many of them traveled widely and did so purposely. In some cases, this was pressed by conditions of war or oppression. But in many others, it was freely chosen in the pursuit of either intellectual adventure or the chance for diverse learning from different teachers. Hippocrates, al-Haytham, Shen Kuo, and Adelard of Bath are all notable examples.

Knowledge is mobile because people have been travelers, ambitious students of nature and the world. Such would seem one more reality that connects the present and future to the past.

Theme 8: science and art

In this book we have encountered the bond between science and image-making many times. We have seen it at work in settings as different as ancient Egypt, Tang Dynasty China, and Renaissance Europe. Science and art thus have ancient connections and mutual dependencies. Being able to document and to record the natural world are inevitably aligned, though the parallelisms are not always obvious.

Creations of art, like paintings and sculpture, can tell us a great deal about how a past civilization viewed the natural world. They may show us technologies or technical processes, such as those related to agriculture, irrigation, medical practice, the calendar. They can also reveal aspects of the imagination, how images were used to record phenomena and project meaning. Think, for example, of astronomical signs embodied in architectural structures, such as the fire altars of Vedic India or the pyramids and temples of the Maya.

Then there is the role that images have played in science itself. Here, we need to include mathematical diagrams, illustrations, anatomical pictures, drawings of instruments, maps of the Earth and the heavens, and much more. Clearly, there is a long and fascinating history here, too. It is a history that goes hand-in-hand with the technology of image-making. Think, for example, of mathematical drawings in works from China, India, Greece, Islam, and Europe: there were very few early on, but they began to grow in number and complexity over time, with the invention of paper, woodblock printing, and finally moveable type. With the "age of exploration" in Europe and the advent of the printing press, the universe of technical imagery fairly exploded. Moreover, artists were contracted for these voyages to visually document new flora, fauna, and phenomena, so that any boundaries between "scientific" and "artistic" disappeared. There was, too, the authority now granted to map-making in terms of recreating the world in visual form and embodying the new powers of the exploring, colonizing eye.

Scholars, therefore, have discovered that important historical meanings are exposed by the what, how, why, where, and when of images. It is quite striking, for example, to see the native peoples of the Americas drawn as elegant Renaissance nudes in books published to gain large profits in Europe during the 16th and 17th centuries. It is no less so when these graceful nudes are shown dismembering, roasting, and eating their Spanish visitors.

Theme 9: the science and the "classic"

What can be considered a "classic" of science? A typical answer today would be Darwin's *Origin of Species*. But, as we have seen, the most canonical works in the history of world science came from the pre-modern era, as far back as Han Dynasty China.

This idea of the "classic" as a work of eternal value had great importance for Chinese thinkers. It was embodied in the *Wujing* (Five Classics), the body of Confucian works considered the complete foundation for the educated citizen. It also came to surround works like the *Yellow Emperor's Classic of Internal Medicine* and the *Nine Chapters on the Mathematical Art*, in regular use for at least 1,800 years. These attracted an entire literature of interpretive commentary, expanding on the originals which otherwise had an immobile, even sacrosanct, quality.

Are there parallels in other civilizations? For India and the *Vedas*, the answer is clearly yes. More than the *Wujing*, these were explicitly religious and sacred. Later came the *Aryabhatiya*, probably the most influential single work in Indian astronomy, whose sophisticated poetic code needed interpretive commentaries, too. For Islam and Europe, the idea of the "classic" was more dynamic. Works like the *Almagest* were held to be foundational from the 9th to the 17th centuries. Moreover, they, too, came to rest on a bed of commentary, like the *Nine Chapters* and *Aryabhatiya.* Yet there were essential differences. First, they were foreign texts; status was given to translations. Second, this status did not remain intact. Within only a few centuries, Greek science began to draw criticism, both in Islam and Europe. In Europe, it even came to be seen as the adversary to progress, i.e. "anti-classics." The "ancients" had to give way to the "moderns," whose works are today considered the true canon of science.

For pre-modern science, then, the "classic" served varied purposes. Great power was invested in certain works that could set high standards for knowledge. Transformed into reverence, however, such power drew valuable commentary but also stasis, even stagnancy, which, in some cases, led to overthrow and replacement with more advanced "classics."

Theme 10: the Needham question

Joseph Needham, the great scholar of China's history of science, has his name affixed to a famous question. In Needham's own words: "Why did modern science develop only in the Western world?" It has also been phrased in a negative way: why *didn't* modern science develop in China or Islam or India?

We lack the space to evaluate even the main responses so far given. A few comments, however, can be made. One view has focused on economic and political conditions, such as the lack of status given the merchant class in China. Another blames religion in the case of Islam, and, in India, repeated foreign invasion. By such reckonings, Europe ended up the only remaining possibility. This is far better than the idea (common until the late 20th century) that only Europe ever possessed something called "the scientific spirit." But it still leaves much room for other, less occult, interpretations.

This book clearly sides with those who believe a number of factors were involved. It would also emphasize that these factors are intellectual in nature, as well as cultural and political. Several of the main factors, in fact, would include the following:

1 Between roughly 1100 and 1300, Europe absorbed the most advanced scientific and technological knowledge the world had to offer. This included the overwhelming majority of knowledge generated by Islam's "golden age" and also the most epochal innovations of Song Dynasty China.
2 Institutional supports were strong and hurdles small to adopting, teaching, and furthering this knowledge. With few exceptions, the Catholic Church remained a primary support to such activity.

3 The new knowledge impacted other domains like theology, literature, architecture, and art. In various ways, transformations in these domains came to aid the advance of science, as in the uses of Renaissance art for documenting phenomena.
4 Europe never suffered an invasion interrupting its intellectual life and destroying its institutions. It continued to build a scientific culture, like the one that existed in early Islam, shared through the Latin language.
5 Europe benefited enormously from the impacts of moveable-type printing. This standardized texts, made books cheap, speeded up publication, and encouraged authorship. Such had huge significance for education, study, and writing of science.
6 Europe pursued overseas voyages that exposed its scientific culture to the greater world, bringing a flood of new phenomena, new realities, and new knowledge. This weakened uncritical veneration for ancient texts, promoting new views and ideas.

Theme 11: the history of science is still a young field

Readers of this book will have learned that the history of pre-modern science should have a rich and brilliant future. The reason is clear: a huge number of materials have yet to be studied. This is particularly true for texts in Arabic and Sanskrit, but it may well include ancient material in China, the Indus Valley, the Americas, and even Europe.

Thousands of medieval manuscripts dealing with Muslim science are present across the Middle East and North Africa and perhaps in Central Asia. This material exists in private collections, small museums, university and government archives, and other local institutions. It is almost certain that some of it, if gathered and preserved, will alter our interpretations about Islam's "golden age." Portions of it may well include the lost volumes of famous thinkers, new translations of Greek, Persian, or Hindu works, or other texts of importance. We simply do not know what might be revealed.

In India, over five million manuscripts, many from the medieval period and earlier, are estimated to exist in the country and overseas collections. Most are on palm leaves, highly vulnerable to decay, so the condition of such texts will be variable. The manuscripts undoubtedly take up many subjects, from Buddhist sutras to legal decrees, yet past collections indicate that scientific works are abundant. The Indian government and private donors have taken steps to collect and preserve many manuscripts. A National Mission for Manuscripts program established in 2003 has developed a network of centers for finding, receiving, and digitizing texts. By early 2015, more than three million manuscripts had been documented – though not yet studied.

The history of science remains a young discipline. This is especially true when looked at from a global perspective. If a majority of scholarship has so far been concentrated on Europe, we can imagine that this will change with time.

Theme 12: science has always been international

Starting from the earliest periods of civilization, science was a diverse, pluricultural endeavor. Each scientific culture emerged from its own particular setting and was, therefore, an expression of the people who created it. At the same time, there is the historical fact of influence among these cultures. This has meant, over time, that each civilization has selectively absorbed and nativized elements from other scientific cultures, making each "pluricultural" in a sense.

This returns us to Francis Bacon and our mention of him in Chapter 1. His ignorance regarding the origins of those "three discoveries" he felt to be epochal in human history we now can better understand. We still do not know exactly how the compass, gunpowder, and printing (which we would combine with paper) came to Europe, after all. Yet it is more difficult to forgive Bacon for dismissing *any* contribution from foreign peoples. It seems to be a sign that European scientific culture had the capability to forget or ignore its own past.

In the year 1620, Bacon published *The Great Instauration*, a work of no small ambition. By "instauration" Bacon meant a renewal, even a great repairing, of existing knowledge. It would involve a new division of the sciences, a new method for scientific work, a record of what phenomena had been studied, all ideas that Muslim thinkers and others before them had used. Indeed, if Bacon had written today, with his desire for new understandings, he might well have taken up different subjects.

Seeing how far the sciences have come in the 21st century, he might then have turned to history. He might show us how many of the great discoveries and innovations that helped build the modern world – from gunpowder to rubber, and from clinical trials to the skeptical mind – came from scientific cultures distant to Europe's shores. He might tell us, therefore, that Europe's own great scientific bounty began with collecting the knowledge of many peoples and places, and, after fruitful struggles, used this diverse material as the substance for transformation. There is a certain justice, he would finally say, in the modern sciences having now overflowed their crucible. That, in the 21st century, they have come to be pursued by men and women in every major culture of the world matches the truth of their origins.

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