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To Emin Saatçi, Memo and Anne Marie Sağıroğlu

LIGHT FROM THE EAST

How the Science of Medieval Islam Helped to Shape the Western World

John Freely

I.B. TAURIS
LONDON · NEW YORK

Published in 2011 by I.B.Tauris & Co Ltd
6 Salem Road, London W2 4BU
175 Fifth Avenue, New York NY 10010
www.ibtauris.com

Distributed in the United States and Canada Exclusively by
Palgrave Macmillan
175 Fifth Avenue, New York NY 10010

ISBN 978 1 84885 452 9

A full CIP record for this book is available from the British Library
A full CIP record is available from the Library of Congress
Library of Congress Catalog Card Number: available

Typeset in New Baskerville by Dexter Haven Associates Ltd

Printed and bound in Sweden by Scandbook

CONTENTS

LIST OF PLATES

PLATES ARE BETWEEN PAGES 114 AND 115

PROLOGUE

The Scriptorium at the Süleymaniye

The Süleymaniye mosque in Istanbul, built by the architect Sinan for Sultan Süleyman the Magnificent in the years 1550–56, is the most splendid of the Islamic monuments that adorn the former capital of the Ottoman Empire. The mosque is the centre of a vast complex of pious foundation that also includes half-a-dozen madrasas (Arabic), a hospital, an insane asylum, a refectory, a caravansarai, a primary school, a public bath, a market, and the tombs of Süleyman and his wife Roxelana. The Ottoman Turks reached their peak under Süleyman, who ruled from 1520 until 1566, his realm extending from the Danube to the Nile and from the western Mediterranean through the Middle East. Their sultanate endured until 1923, the last of the great Muslim empires that emerged with the rise of Islam in the seventh century.

Many of the institutions of the Süleymaniye complex have been restored, though only the public bath still serves its original function. The hospital is now a maternity clinic, the primary school houses a children's library, the refectory has been converted into a restaurant specialising in Ottoman cuisine, and one of the madrasas is a library, whose scriptorium contains several thousand manuscripts, many of them works of medieval Islamic science.

Some years ago I spent a day at the scriptorium of the Süleymaniye examining medieval manuscripts of Islamic science with the curator, Muammer Bey. I looked at Arabic translations of ancient Greek classics in science and philosophy, including works of Aristotle, Archimedes, Euclid, Galen and Ptolemy, along with Islamic treatises in philosophy, physics, mathematics, astronomy, medicine, geography, astrology and alchemy, many of them illustrated with beautiful miniatures. Most of the texts dated from the ninth century to the twelfth, the golden age of Islamic science.

When Europe was shrouded in the relative darkness of the Middle Ages following the end of Graeco-Roman civilisation, Arabic astronomers were observing the heavens from observatories in Samarkand, Baghdad, Damascus, Cairo, Marrakech and Cordoba, where Islamic physicians, philosophers, physicists, mathematicians, geographers and alchemists were pursuing their researches, preserving and extending the knowledge that they had obtained principally from the ancient Greeks, with some contributions from ancient Mesopotamia, Sasanian Persia, India and China. It was through these men of science and learning that knowledge gained in the Islamic world passed to Europe, beginning as far back as the ninth and tenth centuries. Translations from Arabic to Latin inspired the developments that led to the scientific revolution of the sixteenth and seventeenth centuries, with the theories and discoveries of Copernicus, Kepler, Galileo and Newton. Islamic scholars continued to do original work up to the middle of the sixteenth century, particularly in astronomy, creating geometric models that fit the observed phenomena of planetary behaviour better than those designed by Ptolemy and which in turn influenced Copernicus. They continued to debate the great question of whether the earth moved, propose new and revolutionary ideas, create new calculations and design groundbreaking mathematical and astrological models well into the sixteenth century and perhaps even into the seventeenth century in some places. From the fifteenth century, migrants, diplomats, scholars, merchants, missionaries and adventurers from eastern, southern and western Europe flocked to the Ottoman Empire. Some of them brought with them knowledge of Galileo, Descartes and Newton and in turn absorbed Islamic knowledge of mathematics and astrology.

But by the seventeenth century Europe had forgotten its debt to Islam, for although Newton, in saying that he had seen farther than his predecessors 'by standing on the shoulders of Giants', gives credit to earlier European and ancient Greek thinkers, he makes no mention of the medieval Arabic scholars from whom Europe had first learned about science.

Many modern historians of science are beginning to establish the important role that Arabic scientists and philosophers played in the European renaissance and the subsequent scientific revolution. But most of their writings are scholarly works that cover only certain areas of the subject, particularly mathematical astronomy, and none of them has written a comprehensive history of Islamic science for the general reader. This was what prompted me to write *Light from the East.*

The book focuses in turn on several questions. First, what were the factors that led the people of the Islamic world to absorb science and philosophy from the Greeks and other earlier civilisations, including Mesopotamia, Persia, India and China? Aside from preserving the science that they acquired, did the scientists and scholars of the Islamic world make any original contributions? What were the factors in these Islamic societies that led to the eventual decline in Arabic science in most areas and why did certain disciplines such as philosophy, arithmetic and astrology continue to flourish long after the others had become moribund?

The book is also a cultural travelogue that takes the reader in turn from ancient Mesopotamia and Egypt to classical Athens and Hellenistic Alexandria, ʻAbbasid Baghdad, Ayyubid Cairo and Damascus, Almoravid Marrakech and Cordoba, Ilkhanid Persia, Timurid Samarkand.

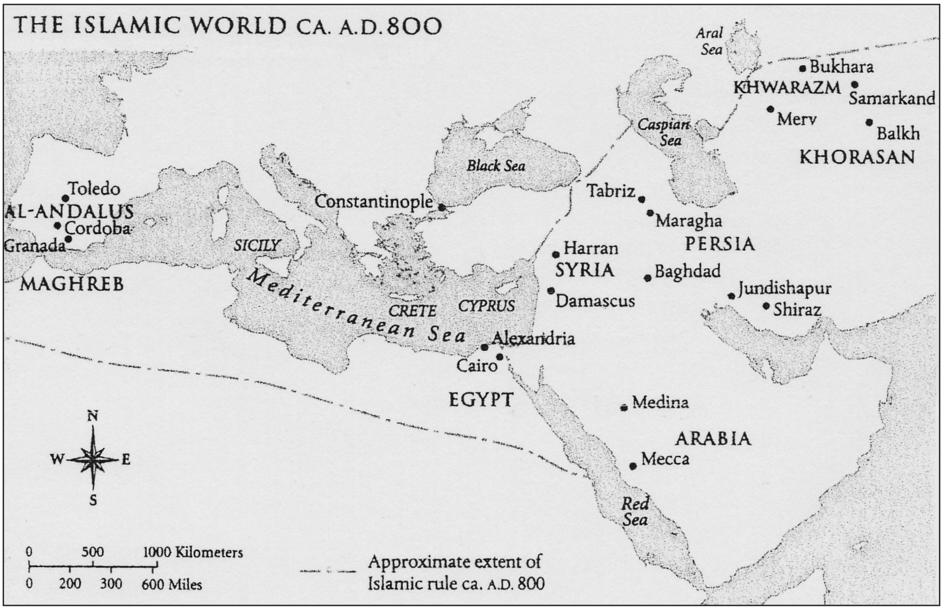
The scope of Islamic science was immense, as one can see from a genre of Arabic works in popular science dealing with the infinite marvels of divine creation. This immensely broad definition of scientific knowledge is evident in the works of the most renowned Islamic scholars, polymaths who wrote on many different areas within and beyond the traditional bounds of science, including the occult pseudo-sciences of alchemy, astrology, number mysticism and magic.

The very names Islamic and Arabic as associated with the word ‘science’ require some discussion. The science that emerged and flourished in the medieval Islamic world was looked upon as ‘foreign’ by Muslim scholars, since it had largely been imported from the Greeks, in contrast to branches of learning such as the study of the Qu’ran, the traditions of the Prophet, Sharia law, orthodox theology, Persian poetry and the Arabic language. Most of the scientists in the Islamic world were Muslims, but there were a number of Christians and Jews and even a few who adhered to a form of an ancient Mesopotamian astral religion. Most of them wrote in Arabic, but a survey of extant Islamic scientific manuscripts by Boris A. Rozenfeld and Ekmeleddin Ihsanoğlu records works in Persian, Syriac, Sanskrit translated into Persian, Tajik, Turkik Urdu, Tatar, Uzbek and other Asiatic languages. But whatever their religion, ethnic origin or language, they were part of the Islamic world, just as western scholars of the late medieval era belonged to the Latin Christian world, while those of the Byzantine Empire, with its capital in Constantinople, were largely Greek-speaking Orthodox Christians who still retained a link with ancient Graeco-Roman culture.

The survey by Rozenfeld and Ihsanoğlu records the extant manuscripts of 1,711 works of scientists from the Islamic world, along with 1,376 works whose authors are unknown. The subject headings under which the works are classified include mathematics, astronomy, mechanics, physics, music, mathematical geography, descriptive geography, chemistry and alchemy, mineralogy, meteorology, zoology, botany and philosophy, not to mention astrology, magic and the many forms of divination. Only a very small number of these works have been studied and published in modern translations, but the survey by Rozenfeld and Ihsanoğlu gives a brief summary in English of the contents of each one of the manuscripts.

These works are preserved in the libraries of cities in fifty countries, including sixteen in Istanbul alone, the most important collection being that of the scriptorium of the Süleymaniye, where I first became aware of the rich heritage of Islamic science.

This, then, is a story of how science emerged and developed in the Islamic world, and of how elements of this knowledge were transmitted to Europe at the dawn of the Renaissance, changing the world forever.


THE ISLAMIC WORLD CA. A.D. 800
Aral Sea
Bukhara
KHWARAZM
Samarkand
Merv
Balkh
KHORASAN
Caspian Sea
Black Sea
Toledo
AL-ANDALUS
Cordoba
Granada
MAGHREB
Constantinople
SICILY
Tabriz
Maragha
PERSIA
Harran
SYRIA
Baghdad
Jundishapur
Shiraz
Damascus
Mediterranean Sea
CRETE
CYPRUS
Alexandria
Cairo
EGYPT
Medina
ARABIA
Mecca
Red Sea
N
W
E
S
0
500
1000 Kilometers
0
200
300
600 Miles
Approximate extent of Islamic rule ca. A.D. 800

CHAPTER 1

Science Before Science: Mesopotamia and Egypt

The Greeks of the classical era believed that they had acquired their knowledge of astronomy from Mesopotamia and Egypt. Herodotus credits the Babylonians with inventing the gnomon, the shadow-marker of the sundial, which the Greeks used in determining the hours of the day and the seasons of the year. He writes that 'knowledge of the sundial and the gnomon and the twelve divisions of the day came into Greece from Babylon.' According to Herodotus, 'The Egyptians by their study of astronomy discovered the solar year and were the first to divide it into twelve parts – and in my opinion their method of calculation is better than the Greek.'

Herodotus also attributed to the Egyptians 'The invention of geometry, which the Greeks brought back to their own country.' The idea was that the Egyptians first developed geometry so that they could redivide their land after the Nile valley was inundated by the annual flood. They also would have needed an advanced knowledge of geometry in the design of huge monuments like the pyramids, which so impressed the Greeks when they first saw them after establishing their trading colonies on the Nile delta.

Although Herodotus credits the Egyptians with the invention of geometry, their geometrical knowledge was for the most part restricted to computing the areas of triangles, rectangles, trapezoids, and circles, for which they used the relatively accurate value of 3.16 for π, and for finding elementary volumes, such as that of a truncated pyramid. But, as Otto Neugebauer remarks in his discussion of Egyptian mathematics, abstract geometry, 'in the modern sense of this word, owes very little to the modest amount of basic geometrical knowledge which was needed to satisfy practical ends'. Neugebauer also remarks that: 'Egyptian astronomy had much less influence on the outside world for the very simple reason that it remained throughout its history on an extremely crude level which had practically no relations to the rapidly growing mathematical astronomy of the Hellenistic age.'

The one area in which the Egyptians influenced Greek astronomy was in the use of their calendar, as Herodotus pointed out. The Egyptian civil calendar was a completely practical one, consisting of 12 months of 30 days each, unrelated to the phases of the moon, with five additional days at the end of each year. Neugebauer remarks that 'the Egyptian calendar became the standard astronomical system of reference which was kept alive through the Middle Ages and was still used by Copernicus in his lunar and planetary tables.' He goes on to say that the Egyptian calendar was revived in Persia by King Yazdigerd, just before the Sasanian dynasty fell to the forces of Islam; nevertheless the so-called 'Persian' years of the Yazdigerd era, beginning 632 AD, 'survived and are often referred to in Islamic and Byzantine astronomical treatises'.

The Egyptians originally began their year with the so-called heliacal rising of the star Sothis (Sirius), that is when it rose shortly before the sun, after an interval of about seventy days when it was invisible because of its closeness to the sun when observed from the earth. This had special significance because the heliacal rising of Sothis occurred around the time of the annual flood that inundated the Nile valley. The Egyptian calendar year of 365 days had a systematic error since the time between summer solstices, as measured by the Babylonians, is about 365.25 days. This error amounted to about a day in four years, a month in approximately 120 years, and a whole year in 1,456 years, a period called the Sothic cycle. It was noted in 139 AD that the beginning of the civil year coincided with the heliacal rising of Sothis. And so similar coincidences of the civil and astronomical calendars must have taken place in the past at intervals of 1,456 years; that is, in 1317 BC, 2773 BC, and 4,229 BC Some Egyptologists take 2773 BC as the date when the Egyptian civil calendar was created, while others hold that it was 4229 BC, although some say that the problem of establishing such a reference point is more complex.

The Egyptians divided the region of the celestial sphere along the ecliptic into 36 zones called decans, a Greek word stemming from the fact that each decan spanned ten degrees, one-third of a zodiacal sign. The Egyptians created a star clock in which the heliacal rising of certain bright stars, one in each of the decans, mark the passing of the hours. Since there were 36 decans this would have led to a division of the complete cycle of day and night into 36 hours. But since the reference point for the astronomical year was the heliacal rising of Sirius, which is in summer, when the nights are shortest, only 12 decans can be seen rising during the hours of darkness. Thus the night was divided into 12 hours and likewise the day. Originally the hours were not of equal length and changed with the seasons, but in the Hellenistic period, when Greek culture dominated Egypt, the day was divided into 24 hours of equal length. At the same time the adoption of the sexagesimal system in Greek astronomy led to the division of the hour into 60 minutes and ultimately the further division of the minute into 60 seconds.

One branch of science in which Egypt excelled was medicine. Egyptian medicine is distinguished by the fact that its practitioners recognised physical symptoms as the first signs of disease, whose treatment was based on their experience of previous cases that they had treated and recorded, although magic and religious rites still played a large part in their practice.

The Greeks almost certainly did acquire some geometry from the Egyptians, but they probably learned far more mathematics from the Babylonians, whose widespread commercial activities brought them in contact with the Greek colonies that had been established at the beginning of the first millennium BC along the Aegean coast of Anatolia, and its offshore islands.

The Mesopotamian and Egyptian interest in astronomy stemmed from their astral religions, in which the celestial bodies, the sun, moon, planets and stars, were worshipped as divine. Their mathematical astronomy was developed through the need to coordinate their observations of the heavenly bodies and to create a calendar.

These celestial deities appear in the Babylonian creation epic, the *Enamu Elish*, whose earliest known version dates to about 1800 BC The *Enamu Elish* describes the mythical events that led up to the creation of the world and the birth of mankind, telling of how Anu, god of the upper heavens, aided by his son Marduk, defeated the forces of chaos and created order in forming the universe, which was a flat disc of earth floating in a vast ocean, roofed over with the celestial sphere.

After their victory Marduk was given charge of the world, built the city of Babylon at its centre, and created mankind to populate the earth and serve the gods. Marduk then set in motion the sun, moon and stars, so that by their eternally recurring motions mankind could tell the time of day and night and determine the passing seasons of the year, creating a celestial clock and calendar. Observation of the celestial bodies and the study of their motions became tasks of the Babylonian priest-astronomers, working in the great towers known as ziggurats, which were both temples and astronomical observatories, one of them appearing in the Bible as the Tower of Babel.

Babylonian astronomy was also motivated by the belief that there is an intimate connection between the celestial and terrestrial regions. Because of this events in the celestial sphere, such as eclipses of the sun and moon, were interpreted as signs of things to come on earth. Thus a close study of celestial motions can be a guide to predicting future events on earth, the belief that underlies the pseudo-science of astrology, one of the principal motivations for observing the heavens from antiquity up until the beginning of modern times.

The earliest examples of writing in Mesopotamia, as well as in Egypt, date to about 3300 BC Mesopotamian writing was in cuneiform, or wedge-shaped, script on clay tablets, which hardened quickly and left a permanent record. Most of the known cuneiform tablets with mathematical contents are from the Old Babylonian period, ca. 1800 BC According to Neugebauer, one of those who first studied these tablets, ‘No astronomical texts of any scientific significance exist from this period, while the mathematical texts show the highest levels ever attained in Babylonia.’

There are also a few mathematical texts from the Seleucid period, from around 300 BC to the beginning of the Christian era, when Mesopotamia was ruled by a dynasty founded by one of the successors of Alexander the Great. The level of these texts is comparable to those of the Old Babylonian period, though, as Neugebauer remarks, ‘The only essential progress that was made consists of the “zero” sign in the Seleucid texts.’ Neugebauer notes that the Seleucid period ‘has furnished us with a great number of astronomical texts of a most remarkable character, fully comparable to the astronomy of the *Almagest*’, referring to the famous work written by the Greek scientist Claudius Ptolemaios (Ptolemy) of Alexandria in the mid-second century AD.

The Babylonian mathematical texts are of two types: ‘table texts’ and ‘problem texts’. The most common of the first type are multiplication and division tables, which were evidently used in the education of scribes. According to Neugebauer, there are also ‘tables of square and square roots, of cubes and cube roots, of sums of squares and cubes needed for the numerical solution of certain types of cubic equations, of exponential functions, which were used for the computation of compound interest, etc.’ The latter tables in particular would indicate that the principal motivation in the development of Babylonian mathematics was its application in economics, and this can be seen in some of the problem texts, one of which represents ‘the calculation of the harvest yield of the province of Lagash for the third year recorded in the text'.

The sexagesimal system first came into use in the Old Babylonian era; it was still in use during the Seleucid period, when, according to Neugebauer, 'this method became the essential tool in the development of a mathematical astronomy, whence it spread to the Greeks and then to the Hindus.' This system survives in the modern world in the division of the circle into 360 degrees, where each degree equals 60 minutes of arc measure, and each minute is 60 seconds of arc, as well as in the division of the hour into 60 minutes of time measure, where each minute equals 60 seconds.

The Babylonians were the first to develop place-value notation in mathematics, where the value of a symbol depends on its place in the number. As an example, writing 111 in the decimal system, the same symbol has the value 1 (10 to the power zero), 10 (10 to the power one) or 100 (10 to the power two), depending on where it is placed in the number. In the sexagesimal system the same symbol would be expressed as 60 to the successive powers zero, one, two, etc.

The Babylonians were familiar with the Pythagorean theorem, but as a relationship between numbers rather than one in geometry. Some of the texts deal with problems in geometry, such as finding the radius of a circle that circumscribes an isosceles triangle, or determining the areas of regular polygons. These and other texts led Neugebauer to remark that Babylonian mathematics at its highest level 'can in many respects be compared with the mathematics, say, of the early Renaissance'.

Many of the Babylonian cuneiform tables for multiplication and division are combined with tables of weights and measures needed in everyday commercial life. This was the beginning of metrology, the creation of uniform measures and physical standards of length and weight. Examples of these Mesopotamian measures and their physical standards have survived, notably those in the Museum of the Ancient Orient in Istanbul but also in collections in Chicago, London and Berlin, including bronze bars marked with the different units of length and bronze masses corresponding to weights of various amounts.

The earliest cuneiform astronomical tablets date from the middle of the second millennium BC, when for several years during the reign of Ammisaduqa records were noted of the appearances and disappearances of Venus, the Babylonian Ishtar, who was worshipped as a fertility goddess. The dates are given in the contemporary lunar calendar, an important factor in determining the chronology of the Old Babylonian period. These observations seem to have provided data for omens of things to come, which Neugebauer remarks are 'the first signs of a development which would lead centuries later to judicial astrology and, finally, to the personal or horoscopic astrology of the Hellenistic age'. He notes that there were at least seventy tablets of this sort with a total of some 7,000 omens, extending over several centuries and reaching its final form ca. 1000 BC One tablet records a prediction based on a disappearance and reappearance of Venus in the seventh year of the reign of Ammisaduqa: 'If on the 21st of Ab Venus disappeared in the east, remaining absent in the sky for two months and 11 days, and in the month Arakhsamma on the 2nd day Venus was seen in the west, there will be rains in the land; desolation will be wrought.'

Two texts from ca. 700 BC, though undoubtedly based on older material, contain a summary of the astronomical knowledge of their time. The first deals mostly with the fixed stars, which are arrayed in three zones spanning the celestial equator, with the central one some thirty degrees wide, an early attempt at mapping the heavens. The second tablet concerns the moon and the planets as well as the seasons, the latter determined by observation of shadows cast by a gnomon, the winter and summer solstices occurring when the noon shadow is longest and shortest, respectively, the spring and autumn equinoxes when the sunrise and sunset shadows are due east and west. Neugebauer remarks that 'The data on risings and setting [of the stars], though still in a rather schematic form, are our main basis for the identification of the Babylonian constellations.'

Tablets from ca. 700 BC contain systematic observations of court astronomers who served the Assyrian emperors. The observations recorded in these tablets include eclipses of the sun and moon, where it was noted that solar eclipses only occurred at the time of new moon, the end of a lunar month, while lunar eclipses took place when the moon was full, in the middle of the month. The Greek astronomer Ptolemy would seem to have had access to this data, for he notes that he had records of eclipses dating back to the time of Nabonassar (747 BC).

Twelve constellations, known to the Greeks as the signs of the zodiac, each of them about thirty degrees wide, were chosen to chart the progress of the sun in its yearly motion through the stars. Greek astronomers of the Hellenistic era defined the sidereal year, the time taken by the sun to make one complete circuit of the zodiac. The month was measured by observing the lunar cycle from new moon to full moon and back to new moon again. New moon is when the moon is between the earth and sun so that it is showing its dark side; full moon is when it is on the far side of the earth from the moon and its full disc is visible. The point of this cycle that is easiest to observe is the first crescent, which appears a day or two after new moon above the western horizon after sunset. One lunation, a lunar month, is the time between two successive appearances of the first crescent, which can be either 29 or 30 days, averaging about 29.5 days over the course of 12 months. Twelve lunar months is equal to approximately 354 days. Thus a purely lunar calendar, such as the one generally used in the Islamic world, will fall out of phase with the year of the seasons by close to 11.25 days each year. At first the Babylonians adjusted for this by adding a thirteenth month every three years or so. Then, early in the Seleucid period they devised a scheme that the Greeks called the Metonic cycle, in which there were 12 ordinary years of 12 months each interspersed with 7 intercalary lunar years of 13 months each. This cycle produced the calendar of Seleucid Mesopotamia, which had an error of only one day in 350 years, as measured by the predicted appearance of a new moon. The Metonic cycle also formed the basis for the Jewish and Christian calendars as well as two of the earliest astronomical calendars of India.

An advance in mathematical astronomy made during the Seleucid period was the introduction of the great circle in the celestial sphere known as the ecliptic, which traces the path of the sun among the fixed stars. This was the first step in mapping the heavenly bodies on the celestial sphere, a procedure that was fully developed by Greek astronomers of the Hellenistic period.

Another advance made during the Seleucid period was the ability to predict whether a given month would have 29 or 30 days. The Babylonian scribes solved this problem by recording the lengths of the passing months over a very long period of time and identifying the factors, such as the angle of the ecliptic with the horizon, that determined whether a lunation would be 29 days or 30. They did this by a study of the various cycles involved, the earliest example of a scientific theory, the collection of observational data that was subjected to mathematical analysis to predict a measurable result. A similar analysis was made of the synodic periods of planetary motions, that is the time of recurrence of their cyclical motions as seen from the earth. The tables of observations that provided the dates for these studies were almanacs which the Greeks called ephemerides. These are represented by somewhat less than 250 cuneiform tablets, more than half of which are lunar and the rest planetary, according to Neugebauer, who notes that there are also about seventy tablets describing the mathematical procedures for analysing this data.

Neugebauer, in summarising his discussion of Babylonian mathematics and its influence on Greek mathematicians and those of later civilisations, concludes that 'All that we can safely say is that a continuous tradition must have existed, connecting Mesopotamian mathematics of the Hellenistic period with contemporary Semitic (Aramaic) and Greek writers and finally with the Hindu and Islamic mathematicians.'

The spread of astrological belief was the principal reason for the transmission of astronomical knowledge from one culture to another, such as from Mesopotamia to the Greek world and then to India. Neugebauer also noted that 'the terminology as well as the method of Hindu astrology are clearly of Greek origin; for example the names of the zodiacal signs are Greek loan words.' He also remarked that 'it seems reasonable to assume that Babylonian methods, parameters and concepts reached India in two ways, either via Persia or the Roman sea routes, but only through the medium of Hellenistic astronomy and astrology.'

The system used in Babylonian astrology had each day 'ruled' by one of the seven moving celestial bodies, i.e., the sun, moon and five planets. The order in which these bodies appear in Babylonian horoscopes is Sun – Moon – Jupiter – Venus – Mercury – Saturn – Mars. Greek horoscopes had them in the order Sun – Moon – Saturn – Jupiter – Mars – Venus – Mercury. Eventually this changed to the order that is used in modern horoscopes: Sun – Moon – Mars – Mercury – Jupiter – Venus – Saturn, an arrangement that gave the days of the week their names in the European languages.

The Babylonian astronomer Berossos, who moved to the Greek island of Cos ca. 270 BC, may be a direct link in the transmission of Mesopotamian knowledge to the Greeks, but his fragmentary extant works contain no writings on mathematical astronomy. Nevertheless, as Neugebauer remarks, 'Babylonian influence is visible in two different ways in Greek astronomy; first, in contributing basic empirical material for the geometrical theories we have outlined…; second, in a direct continuation of arithmetical methods which were used simultaneously with and independently of the geometrical methods.'

The Babylonian mathematics and astronomy that was absorbed by the Greeks was passed on in turn to the Arabs, some of it, as we will see, through the Hellenised people of south-eastern Anatolia and Mesopotamia, and some through the Hindus after they acquired it from the Greeks, such was the ebb and flow of knowledge through the interconnected cultures of East and West.

CHAPTER 2

The Land of the Greeks

One of the early Islamic scientists, Hunayn ibn Ishaq, writes of going off to *bilad-al-Rum*, 'the land of the Greeks', where he improved his Greek in order to read scientific manuscripts that he eventually translated into Syriac and then into Arabic. The land of *Rum* was for him Greek-speaking Asia Minor and Constantinople, capital of the Byzantine Empire.

Around the beginning of the first millennium BC there was a great migration that took the Greeks from their homeland in south-eastern Europe across the Aegean to the western coast of Asia Minor and its offshore islands. Three Greek tribes were involved in this migration: the Aeolians to the north, as far as the Hellespont, south of them the Ionians, and farther to the south the Dorians. Together they produced the first flowering of Hellenic culture, the Aeolians giving birth to the lyric poets Sappho and Alcaeus, the Ionians to the natural philosophers Thales, Anaximander and Anaximenes, and the Dorians to Herodotus, the Father of History.

Herodotus tells us that the Ionian cities organised themselves into a confederation called the Panionic League, which comprised the islands of Samos and Chios and ten cities on the mainland of Asia Minor opposite them: Phocaea, Clazomenae, Erythrae, Teos, Lebedus, Colophon, Ephesus, Priene, Myus and Miletus. Miletus surpassed all of the other Greek cities of Asia Minor in its maritime ventures, founding colonies around the shores of the Black Sea as well as along the Hellespont and on the Nile delta. Other cities, most notably Phocaea, established colonies along the western shores of the Mediterranean, particularly in southern Italy and Sicily, which became known as Magna Graecia, or Great Greece, because of the number of Hellenic settlements there.

Miletus was the birthplace of Thales, Anaximander and Anaximenes, who flourished in turn during the first half of the sixth century BC Aristotle refers to them as *physikoi*, from the Greek *physis*, meaning 'nature' in its widest sense, contrasting them with the earlier *theologoi*, or theologians, for they were the first who tried to explain phenomena on natural rather than supernatural grounds.

The most enduring idea of the Milesian philosophers proved to be their belief that there was an *arche*, or fundamental substance, which was at the basis of all matter, enduring through all apparent change. Thales believed that the *arche* was water, which is normally liquid but when heated appears in the gaseous state as steam and when frozen is solid ice. Anaximander called the fundamental substance *apeiron*, or the 'boundless', meaning that it was not defined by having specific qualities. Anaximenes held that the *arche* was *pneuma*, meaning 'air' or 'spirit', which assumes various forms through its eternal motion.

Ionia was also the birthplace of Pythagoras, who was born on Samos in the mid-sixth century BC and moved to the Greek colony of Croton in southern Italy.

There, it is believed – though we cannot be certain – that he founded a philosophical school and mystical sect, whose beliefs included that of *metempsychosis*, or the transmigration of souls. Pythagoras and his followers are credited with laying the foundations of Greek mathematics, particularly geometry and the theory of numbers. The most famous of their supposed discoveries is the Pythagorean theorem, which states that in a right triangle the square on the hypotenuse equals the sum of the squares on the other two sides. As we have noted, the Babylonians were aware of this a thousand years earlier, but as a relationship between numbers rather than a geometrical theorem.

According to tradition, their experiments with stringed instruments led the Pythagoreans to understand the numerical relations involved in musical harmony. This made them believe that the cosmos was divinely designed according to harmonious principles that could be expressed in terms of numbers. According to Aristotle, the Pythagoreans 'supposed the elements of numbers to be the elements of all things, and the whole heavens to be a musical scale and a number'.

The Greek colonies in Magna Graecia rivalled Ionia as a centre of natural philosophy, beginning with the Pythagoreans and continuing with Parmenides and Zeno of Elea in southern Italy, as well as Empedocles of Acragas in Sicily, who flourished around the same time as the Milesian physicists.

Parmenides denied the possibility of motion and any other kind of change, which he said were mere illusions of the senses. The philosophy of Parmenides was defended by his follower Zeno, who proposed several paradoxes designed to show that examples of apparent motion are illusory. Empedocles agreed with Parmenides that there was a serious problem regarding the reliability of our sense impressions, but he said that we are utterly dependent on our senses for they are our only direct contact with nature. Thus we must carefully evaluate the evidence of our senses to gain true knowledge.

Empedocles proposed that everything in nature is composed of four fundamental substances, earth, water, air and fire. The first three of these correspond, albeit superficially, to the modern classification of matter into three states of matter, earth representing solids, water liquids, and air gases, while fire for Empedocles represented not only flames but phenomena such as lightning and comets. According to Empedocles the four substances alternately intermingled and separated under the influence of what he called Love and Strife, corresponding to the modern concept of attractive and repulsive forces.

A radically different theory of matter was proposed in the mid-fifth century BC by Democritus of Abdera, a Thracian city founded by Ionians from Teos. Democritus thought that the *arche* exists in the form of atoms, the irreducible minima of all physical substances, which through their endless motion and mutual collisions take on all of the many forms of matter observed in nature. Democritus seems to have learned the theory from his teacher Leucippus, whose only extant fragment states that ‘Nothing occurs at random but everything for a reason and by necessity’, by which he meant that the motion of the atoms is not chaotic but obeys the immutable laws of nature.

The history of Greek medicine begins with Hippocrates, who was born on the island of Kos ca. 460 BC The writings of Hippocrates and his followers, the so-called Hippocratic Corpus, comprises some seventy works dating from his time to ca. 300 BC. They include treatises on all branches of medicine as well as clinical records and notes of public lectures on medical topics. A treatise on Deontology, or Medical Ethics, contains the famous Hippocratic Oath, which is still taken by physicians today.

Athens became the cultural centre of the Greek world during the classical period, 479–323 BC, which began with the end of the Persian Wars and ended with the death of Alexander. The first philosopher to reside in the city was Anaxagoras (ca. 520–ca. 428 BC) of Clazomenae, who left Ionia at the age of twenty and moved to Athens, where he resided for thirty years, becoming the teacher and close friend of Pericles.

Anaxagoras believed that the cosmos had a directing intelligence that he called *Nous*, or Mind, as Plutarch writes of him in his *Life of Pericles*: 'he was the first to enthrone in the universe not Chance, nor yet Necessity, but Mind (*Nous*) pure and simple, which distinguishes and sets apart, in the midst of an otherwise chaotic mass, the substances which have like elements.'

Anaxagoras believed that the cosmos was filled with an invisible element called the aether, which is in constant rotation and carries with it the celestial bodies. He says in one of his surviving fragments that 'The sun, the moon and all the stars are red-hot stones which the rotation of the aether carries round with it.' The nebulous concept of the aether proved to be very enduring, and it keeps reappearing in cosmological theories, as in the nineteenth century when it was thought to be the medium that transmits the electromagnetic force.

The intellectual life of classical Athens was dominated by its two famous schools, the Academy of Plato and the Lyceum of Aristotle. The Academy was founded by Plato ca. 380 BC and functioned more or less continuously until 529 AD, when it was closed by the emperor Justinian. Aristotle was a student at the Academy during the last twenty years of Plato's life, and then in 335 BC he founded the Lyceum, which he directed until 324 BC, when he returned to his native Macedonia, a year before he died.

Plato's attitude toward the study of nature is evident from what he has Socrates say in his dialogues. In the *Phaedo*, Socrates tells of how he had been attracted to the ideas of Anaxagoras because of his concept of *Nous*. But he was ultimately disappointed, he says, when he 'saw that the man made no use of Mind, nor gave it responsibility for the management of things, but mentioned as causes air and aether and water and many other strange things'.

Socrates was dissatisfied with Anaxagoras and the other early natural philosophers, because they only told him *how* things happened rather than *why*. What he was searching for was a teleological explanation, for he believed that everything in the cosmos was directed toward attaining the best possible end. Plato's most enduring influence on science was his advice to approach the study of nature as an exercise in geometry, particularly in astronomy. Through this geometrisation of nature, applicable in disciplines such as astronomy that can be suitably idealised, one can arrive at laws that are as 'certain' as those in geometry. As Socrates says in the *Republic*, 'Let's study astronomy by means of problems as we do in geometry, and leave the things in the sky alone.'

The problem for Greek astronomers was to explain the motion of the celestial bodies – the stars, sun, moon and the five visible planets – as seen from the earth, which was believed to be the immobile centre of the cosmos. When these bodies are observed from the earth they appear to be embedded in a globe called the celestial sphere, which seems to rotate daily about a point in the heavens called the celestial pole. This apparent motion is actually due to the rotation of the earth in the opposite direction, the projection of its axis of rotation among the stars forming the celestial pole. The axial rotation of the earth makes it appear as if the sun rises in the east each day and sets in the west. At the same time the orbital motion of the earth around the sun makes it appear as if the sun moves back from west to east among the stars a little less than one degree per day, completing a circuit of the twelve signs of the zodiac in one year. The path of the sun among the stars is called the ecliptic, because solar and lunar eclipses occur when the orbit of the moon crosses the plane of the ecliptic. The ecliptic makes an angle of about 23.5 degrees with the equator of the celestial sphere, due to the fact that the spin axis of the earth is tilted by that amount with respect to the plane defined by its move around the sun. The points where the ecliptic crosses the celestial equator are the spring and fall equinoxes, and the points where it is farthest north and south are the summer and winter solstices, respectively. The five visible planets are also seen to move close to the ecliptic, periodically exhibiting retrograde motion that makes them seem to trace out loops in their motion around the celestial sphere. This happens whenever the planets and the earth pass one another in their orbits around the sun, all of them rotating in the same sense, the inner planets moving more rapidly than the earth and the outer ones more slowly, the effect in both cases making it appear as if the planet is moving backwards for a time among the stars.

Plato believed that all of the celestial bodies were moving with uniform circular motion around the earth, and so, according to Simplicius, a commentator of the sixth century AD, he proposed that astronomers direct their researches to find ‘on what hypotheses the phenomena concerning the planets could be accounted for by uniform and ordered circular motions.’

The astronomer Eudoxus of Cnidus, a younger contemporary of Plato at the Academy, sought to solve the problem by assuming that the path of every celestial body was the resultant motion of four interconnected spheres, all of them centred on the earth, but with their axes inclined to one another and rotating at different speeds. This system may subsequently have been adopted by Aristotle as the physical model for his cosmos, using a total of fifty-six spheres for the celestial bodies, the outermost one containing the fixed stars.

Aristotle's writings are encyclopaedic in scope, covering the entire spectrum of philosophy and science. The dominant concept in his philosophy of nature is the principle of teleology, the idea that natural processes are directed toward an end, which he states most clearly in the second book of his *Physics*:

> Now intelligent action is for the sake of an end; therefore the nature of things also is so: and as in nature. Thus if a house, e.g., had been a thing made by nature, it would have been made in the same way as it is now by art; and if things made by nature were made also by art, they would come to be in the same way as by nature.

Aristotle's cosmology and his theories of matter and motion distinguish between the 'Two Orders of Things', the imperfect and transitory terrestrial world below the sphere of the moon and the perfect and unchanging celestial region above. He adopted the four elements of Empedocles as the basic terrestrial substances, with concentric spheres of earth, water, air and fire, the latter extending out to the sphere of the moon, while he took the aether of Anaxagoras as the *arche* of the celestial bodies. The natural movement of earth, water, air and fire was up or down to their natural place among the terrestrial spheres, while the celestial bodies were carried in uniform circular motion around the stationary earth by their aetherial spheres.

Heraclides Ponticus, a contemporary of Aristotle who had also studied at the Academy under Plato, was the first to suggest that the apparent nightly rotation of the stars is actually due to the rotation of the earth on its axis, though the idea never gained general acceptance in the Greek world.

Aristotle was succeeded as head of the Lyceum by his associate Theophrastus (ca. 371–ca. 287 BC) of Erisos on Lesbos. Theophrastus was as prolific as Aristotle, and Diogenes Laertius ascribes 227 books to him, most of which are now lost. Two of his extant works, the *History of Plants* and the *Causes of Plants*, have earned him the title Father of Botany, while his book *On Stones* represents the beginning of geology and mineralogy.

Theophrastus was succeeded in turn as head of the Lyceum by Straton of Lampsacus on the Hellespont (died ca. 268 BC), who had been his student. Straton is credited with forty works, all of which are lost except for fragments.

Diogenes Laertius describes Straton as 'a distinguished man who is generally known as "the physicist", because more than anyone else he devoted himself to the study of nature'. One of Straton's writings on physics is a lost work *On Motion*, which Simplicius mentions in a commentary on Aristotle. Straton appears to have been the first to demonstrate that falling bodies accelerate, i.e., their velocity increases in time, as Simplicius explains in his commentary: 'For if one observes water pouring down from a roof and falling from a considerable height, the flow at the top is seen to be continuous, but the water at the bottom falls to the ground in discontinuous parts. This would never happen unless the water traversed each successive space more swiftly.'

Early in the Hellenistic period, the new city of Alexandria in Egypt supplanted Athens as the intellectual centre of the Greek world. The intellectual life of Alexandria was focused on two renowned institutions, the Museum and the Library, founded by Ptolemy I Soter (r. 305–283 BC) and developed by his son Ptolemy II Philadelphus (r. 283–45 BC).

The Museum, dedicated to the Muses, the nine daughters of Zeus and Mnemosyne who were the patron goddesses of the humanities, was patterned on the famous schools of Athens, most notably the Academy and the Lyceum. It was more like a research institute than a college, emphasising science rather than the humanities. The scientific character of the Museum was probably due to Straton of Lampsacus, the Physicist, who in the years 300–288 BC served as tutor to the future Ptolemy II, before returning to Athens to succeed Theophrastus as head of the Lyceum.

The organisation of the Library was probably due to Dimitrios of Phaleron, the former governor of Athens, who fled to Alexandria in 307 BC Dimitrios, a former student at the Lyceum in Athens, is believed to have been the first chief librarian of the library, a post he held until 284 BC According to Aristeas Judeus, Dimitrios 'had at his disposal a large budget in order to collect, if possible, all the books in the world, and by purchases and transcriptions he, to the best of his ability, carried the king's objective into execution'. By the time of Ptolemy III Eurgetes (r. 247–21 BC) the Library was reputed to have a collection of half a million parchment rolls, including all the great Greek works in humanities and science from Homer onwards.

The only scientist to serve as chief librarian of the Library was Eratosthenes of Cyrene (ca. 275–ca. 195 BC), a mathematician, astronomer and geographer, who also wrote on literature and history. Eratosthenes was the first to draw a map of the known world based on a system of meridians of longitude and parallels of latitude. He is renowned for his accurate measurement of the earth's circumference, which he determined by observing that the sun's noon shadow at the summer solstice in Alexandria made an angle equal to one-fiftieth of a circle, while on the same day the sun was directly overhead at noon in the city of Syene to the south. He concluded that the distance between Alexandria and Syene was one-fiftieth of the earth's circumference, which he computed by estimating the distance between the two cities and multiplying by fifty, obtaining a result roughly equal to the modern value. Eratosthenes also found that the meridian solar altitude at the summer and winter solstices differed by 11/83 of a circle, which he divided by two to obtain a value of about 23 degrees 51 minutes and 19.5 seconds for the obliquity of the ecliptic.

The great school of mathematics at Alexandria was apparently founded by Euclid, who is believed to have taught at the Museum early in the third century BC, though there are no sources to conclusively prove this. Euclid is renowned for his *Elements of Geometry*, the earliest extant treatise on the subject, translated in turn into Arabic, Latin, and numerous other languages. Euclid's extant writings also include a textbook on astronomy, the *Phenomena*, and a treatise on perspective, the *Optica*. One of the assumptions made by Euclid in the *Optica* is that vision involves light rays proceeding in straight lines from the eye to the object. This erroneous idea, known as the extramission theory, was held by many – though not all – subsequent writers on optics up until the seventeenth century.

Greek mathematical physics reached its peak with the works of Archimedes (ca. 287–12 BC), who was born at Syracuse in Sicily. He corresponded with Eratosthenes, to whom he addressed his famous work *On Method,* lost in antiquity and dramatically rediscovered in 1906. His treatise *On Floating Bodies* is based on the famous Archimedes' Principle, which states that a body wholly or partly immersed in a fluid is buoyed up by a force equal to the weight of the displaced fluid. His book *On the Equilibrium of Planes* uses the law of the lever to find the centre of gravity of various figures, i.e., the point at which all of their weight is effectively concentrated, a concept that became the basis for all subsequent work in statics, the study of mechanical systems in equilibrium. His treatise *On The Measurement of the Circle* uses a technique of successive approximations known as the 'method of exhaustion' to measure the area of a circle. In his treatise *On the Sphere and the Cylinder* he found that ratio of the areas of a cylinder and circumscribed sphere was 3/2, and he was so proud of this discovery that he had the figure inscribed on his tomb.

Archimedes was renowned for his inventions, which included catapults, burning mirrors, a system of compound pulleys for moving large ships on land, and a device for raising water known as Archimedes' Screw, which is still used in Egypt. He also constructed an orrery, or working model of the celestial motions, which was seen by Cicero. According to Pappus of Alexandria, Archimedes wrote a thesis, now lost, describing a celestial globe that he made to represent the motions of the sun and moon and demonstrate solar and lunar eclipses.

In a work called *The Sand Reckoner* Archimedes describes a method for expressing extremely large numbers, which could not be done with the system then used by the Greeks, where numbers were written using letters of the alphabet. As an example, Archimedes computes the number of grains of sand in 'a volume equal to that of the cosmos', which he takes to be a sphere whose radius is the distance between the centres of the earth and sun. He then makes reference to a new astronomical theory that had been proposed by Aristarchus of Samos, a slightly younger contemporary: 'Aristarchus of Samos has, however, enunciated certain hypotheses in which it results from the premises that the universe is much bigger than that just mentioned. As a matter of fact he supposes that the fixed stars and the sun do not move, but the earth revolves in the circumference of a circle about the sun, which lies in the middle of the orbit.'

This is the first mention of a heliocentric theory, eighteen centuries before Copernicus. Cleanthes of Assos, a contemporary of Archimedes, wrote a tract condemning the theory, remarking that Aristarchus should be charged with impiety, on the grounds 'that he was disturbing the hearth of the universe'. Some contemporary classicists consider this passage to be a later addition by a philologist of the seventeenth century, still others believe it to be genuine. The only ancient astronomer known to have accepted the heliocentric theory of Aristarchus was Seleucus the Babylonian, who flourished in the second century BC, but otherwise it was ignored and forgotten until it was revived by Copernicus in the sixteenth century.

The only work of Aristarchus that has survived is his treatise *On the Sizes and Distances of the Sun and Moon*. Here he used geometrical demonstrations together with three astronomical observations to calculate the solar and lunar distances and their sizes relative to the earth. All of his values are greatly underestimated, because of the crudeness of his observations, but he did demonstrate that the sun is much larger than the earth, which may have been the main reason he put it at the centre of the cosmos rather than the earth.

The only other Hellenistic mathematician comparable to Euclid and Archimedes is Apollonius of Perge, born ca. 262 BC, who studied in Alexandria and was an honoured guest in the court of King Attalus I (r. 241–197 BC) of Pergamum in north-western Asia Minor. The only major work of Apollonius that has survived is his treatise *On Conics*, though even there the last book is lost. This is a comprehensive analysis of the four types of conic sections: the circle, the ellipse, the parabola and the hyperbola. *On Conics* was translated in turn into both Arabic and Latin, the latter used by Johannes Kepler in his second law of planetary motion and by Isaac Newton in his analysis of the motion of both planets and terrestrial projectiles.

Apollonius is also credited with formulating two mathematical theories to explain the apparent retrograde motion of the planets. One of these is the epicycle theory, in which the planetary motion is the resultant of two circular motions, one centred on the earth, and the second on the circumference of the first circle, the so-called deferent. The second theory has the planet moving on the circumference of an eccentric circle, i.e., one that is not centred on the earth. He also showed that these two theories were equivalent to one another, so that either one could be used in describing retrograde planetary motion.

Ctesibus of Alexandria, a contemporary of Archimedes, was famous as an inventor of machines, mechanical gadgets and pneumatic devices. Among other things, he is credited with inventing a force pump, a catapult, a fire-engine, an hydraulic organ, a water-clock, and a singing statue, which he made for the empress Arsinoe, sister and wife of Ptolemy II. All of his writings are now lost, but his ideas and inventions were revived by his two most notable followers, Philo of Byzantium and Hero of Alexandria.

The extant writings of Philo, who flourished in the mid-third century BC, comprise three books from a large work on mechanics: *On Catapults, On Pneumatics, and On Besieging and Defending Towns.* In the first of these books Philo states that he travelled to Alexandria and saw a bronze spring catapult made by Ctesibus. This second book described a number of demonstrations almost certainly taken from Ctesibus, including pneumatic toys. The third book, the earliest work on military engineering, describes the use of and defence against various engines of war, as well as the use of secret messages, cryptography and poisons.

Hero of Alexandria flourished ca. 62 AD. His longest extant work by far is the *Pneumatica*, the first chapters of which describe experiments demonstrating that air is a body, evident through the pressure that it exerts, and showing that it is possible to produce a vacuum, contrary to Aristotelian doctrine. The book also describes his famous steam-engine, in which a glass bulb is made to rotate by jets of steam directed tangentially in opposite directions from the two ends of a diameter.

Hero describes other inventions in his treatise *On Automata-Making*, most notably the *thaumata*, or 'miracle-working' devices such as one that opened and closed the doors of a temple using steam generated by fire in an altar. Hero also made important contributions in optics as well as applied mathematics.

Hipparchus of Nicaea, the greatest astronomer of antiquity, flourished in the third quarter of the second century BC What little is known of his life comes from the geographer Strabo, who says that Hipparchus worked in the Library at Alexandria, and from the astronomer Claudius Ptolemaeus, who refers frequently to his theories and observations and often quotes him directly.

All of the writings of Hipparchus have been lost except for his first work, a commentary on the *Phainomena* of Aratus of Soli, a poem describing the constellations. The commentary contains a catalogue of some 850 stars, for each of which Hipparchus gives the celestial coordinates and relative brightness, including those of a ‘nova’ or ‘new star’, which suddenly appeared in 134 BC within the constellation Scorpio.

Hipparchus is renowned for his discovery of the precession of the equinoxes, i.e., the slow movement of the celestial pole in a circle about the perpendicular to the ecliptic. He discovered this effect by comparing his star catalogue with observations made 128 years earlier by the astronomer Timocharis, which enabled him to compute that the annual precession was 45.2 seconds of arc. The currently accepted value is about 50 seconds of arc per year, which gives a precessional period of about 25,800 years. The effect of this precession is to make the tropical year about 20 minutes shorter than the sidereal year.

Hipparchus is also celebrated as a geographer and mathematician, his greatest achievement in the latter field being the development of spherical trigonometry and its application to astronomy, which was continued by Claudius Ptolemaeus.

Theodosius of Bithynia, a younger contemporary of Hipparchus, is known for his *Sphaerica*, a treatise on the application of spherical geometry to astronomy, which was translated into Arabic and Latin and remained in use until the seventeenth century.

Strabo (63 BC–ca. 25 AD) was born in Amasia on the Black Sea coast of Asia Minor and studied in both Alexandria and Rome. His major work is his seventeen-volume *Geography*, which covers the whole of the known world, describing, as he says in his introduction, ‘things on land and sea, animals, plants, fruits and everything else to be seen in various regions’.

The beginning of pharmacology comes with the work of Dioscorides Pedanius, from Anazarbus in south-eastern Asia Minor, who served as a physician in the Roman army during the reigns of Claudius (r. 41–54) and Nero (r. 54–68). His *De Materia Medica* contains a description of some 600 medicinal plants and nearly 1,000 drugs. This was subsequently translated from Greek into Arabic and Latin, becoming the basis for all subsequent work in pharmacology both in Islam and Christian Europe.

Nicomachus of Gerasa (fl. 100 AD) is noted for his *Introduction to Arithmetic*, an elementary handbook on the parts of mathematics that were needed for an understanding of Pythagorean and Platonic philosophy.

His work was translated into both Arabic and Latin in turn, and was influential in both the Islamic world and the West. Menelaus of Alexandria, a contemporary of Nicomachus, wrote on mathematics and made astronomical observations at Rome; his *Spherics*, which applies spherical trigonometry to astronomy, survives only in Arabic.

Ancient Greek astronomy culminated with the work of Claudius Ptolemaeus, known more simply as Ptolemy. All that is known of his life is that he worked in Alexandria during the successive reigns of Hadrian (r. 117–38) and Antoninus Pius (r. 138–61), presumably at the Museum and Library. The most famous of his writings is his *Mathematiki Syntaxis*, better known by its Arabic name, the *Almagest*, a detailed description of the motion of the celestial bodies, based largely on the observations of Hipparchus and using the epicycles and eccentric circles formalised by Ptolemy. The principal modification made by Ptolemy is that the centre of each epicycle moves uniformly (though this is not true for all planets), with respect to a point called the equant, which is displaced from the centre of the deferent, the inner circle, a concept that was to be the subject of controversy in later times. Ptolemy's mapping of the celestial sphere led him to develop spherical trigonometry and the technique of stereographic projection, the basis of the instrument later known as the astrolabe, which Arabic astronomers were to use with great effectiveness.

The extant writings of Ptolemy also include other treatises on astronomy: the *Handy Tables*, *Planetary Hypothese*, *Phases of the Fixed Stars*, *Analemma*, and *Planisphaerium*; a work on astrology called the *Tetrabiblos*, and treatises entitled *Optica*, *Geographia*, and *Harmonia*, the latter devoted to musical theory.

Ptolemy's researches on light are presented in the *Optica*, which is only preserved in a Latin translation of an Arabic translation. His most important accomplishment in this work is the demonstration of an empirical relation for the law of refraction, the bending of a ray of light when it passes from one medium to another, the correct theory for which was not given until the seventeenth century. Neugebauer remarks that 'we see here the progress from a strictly geometrical optics to a theory of binocular vision and physiological optics based on empirical data and systematic experimentation.'

Ptolemy's *Geographia* is the most comprehensive work in theoretical geography that has survived from antiquity, with maps of the known world on a grid of longitudes and latitudes. The *Geographia* was translated into Arabic and then into Latin and served as the basis for all subsequent works on mathematical geography up until the European renaissance.

Galen of Pergamum (130–ca. 204), the greatest physician of antiquity, was a younger contemporary of Ptolemy. He served his medical apprenticeship at the healing shrine of Asclepius at Pergamum, where his work treating wounded gladiators gave him first-hand knowledge of human anatomy, physiology and neurology. After further studies in Smyrna, Corinth and Alexandria he moved to Rome, where he spent most of the rest of his life, serving as physician to the emperors Marcus Aurelius (r. 161–80), Lucius Verus (r. 161–69) and Commodus (r. 180–92).

Galen's writings, translated successively into Arabic and Latin, formed the basis of medical literature in both Islam and Christian Europe up until the seventeenth century. His medical writings are deeply philosophical, including interpretations of Plato, Aristotle, Epicurus and others. This is also evident from the title of one of his treatises, *That the best doctor is also a philosopher*, as well as those of his treatises *On Scientific Proof* and *Introduction to Logic.* He wrote on psychology as well, including the interpretation of dreams, predating Freud by seventeen centuries.

Diophantus of Alexandria (fl. ca. 250 AD) did for algebra and number theory what Euclid had done for geometry and Apollonius for conics. His most important work is the *Arithmetica*, of which six of the original thirteen books have survived. The surviving books of the *Arithmetica* were translated from Greek to Latin in 1621, and six years later they inspired the French mathematician Pierre de Fermat to create the modern theory of numbers.

Pappus of Alexandria, who flourished in the first half of the fourth century AD, wrote works in mathematics, astronomy, music and geography. His treatise entitled *Synagogue* (Collection), is the principal source of knowledge of the accomplishments of many of his predecessors in the Hellenistic era, most notably Euclid, Archimedes, Apollonius and Ptolemy. His own work in mathematics, translated in turn into Arabic and Latin, influenced both Descartes and Newton, and one of his discoveries, known as the Theorem of Pappus, is still taught in elementary calculus courses.

The last scientist known to have worked in the Museum and Library was Theon of Alexandria, who in the second half of the fourth century wrote commentaries on Euclid's *Elements* and *Optica* as well as on Ptolemy's *Almagest* and *Handy Tables.* In the latter work Theon notes that 'certain ancient astrologers' believed that the points of the spring and autumn equinox oscillate back and forth along the ecliptic, moving through an angle of eight degrees over a period of 640 years. This erroneous notion was revived in the so-called 'trepidation theory' of Islamic astronomers, and it survived in various forms up to the sixteenth century, when it was discussed by Copernicus.

Theon's daughter Hypatia was a professor of philosophy and mathematics, and around 400 she became head of the Platonic Academy in Alexandria, the only woman academic in the history of ancient science. She revised the third book of Theon's commentary on Ptolemy's *Almagest*, and she also wrote commentaries on the works of Apollonius and Diophantus, now lost. Her lectures on pagan philosophy aroused the anger of Saint Cyril, bishop of Alexandria, who in 415 instigated a riot by fanatical Christians in which Hypatia was killed.

The Library of Alexandria survived almost to the end of the fourth century, by which time the museum seems to have vanished. The emperor Theodosius I issued a decree in 391 calling for the destruction of all pagan temples throughout the empire. Theophilus, bishop of Alexandria, took this opportunity to lead his fanatical followers in destroying the temple of Serapis, which had housed the Library since the reign of Ptolemy III. The ancient world was coming to an end, though its philosophy and science would eventually be transmitted through the land of the Greeks to the newly emergent world of Islam.

CHAPTER 3

The Roads to Baghdad

The last pagan scholar to head the Platonic academy in Alexandria was Ammonius, who directed it from 485 until his death sometime between 517 and 526. Ammonius was a distinguished philosopher, astronomer and mathematician, known for his commentaries on Aristotle. His most famous students were the mathematician Eutocius of Ascalon and the philosophers John Philoponus and Simplicius of Cilicia. Philoponus, a Christian, succeeded Ammonius as head of the Neoplatonic school in Alexandria. Simplicius, who seems to have remained a pagan, moved to Athens and joined the ancient Platonic Academy.

Eutocius dedicated his commentary on the first book of Archimedes' *On the Sphere and Cylinder* to Ammonius. He later wrote commentaries on two more works of Archimedes – the *Measurement of a Circle* and *On Plane Equilibria* – as well as on the first four books of the *Conics* of Apollonius. His commentaries proved to be crucial in the survival of these works.

Simplicius is famous for his commentaries on Aristotle, which contain much valuable material otherwise unavailable, including fragments of the pre-Socratic philosophers. Some of his Aristotelian scientific ideas were criticised by Philoponus, who had succeeded Ammonius as head of the Platonic school in Alexandria.

Thus in the twilight of antiquity a great debate took place about the Aristotelian world-view, which was attacked by Philoponus and defended by Simplicius. The most interesting part of this debate focused on why a projectile, such as an arrow, continues moving after it receives its initial impetus. Philoponus rejected the Aristotelian theory presented by Simplicius, which was that the air displaced by the arrow flows back to push it from behind, an effect called *antiperistasis.* Instead, Philoponus suggested that the arrow, when fired, receives an 'incorporeal motive force', an idea that was revived in medieval Europe as the 'impetus theory', Philoponus also wrote a treatise on the astrolabe, the instrument later used by all Arabic astronomers for their observations and calculations.

After Constantine shifted the capital of his empire in 330 to Byzantium on the Bosphorus, thenceforth to be called Constantinople, Christianity became the state religion of the realm that later came to be called the Byzantine Empire. Constantine had already organised the first ecumenical council of the church in 325 at Nicaea. The second ecumenical council was held at Constantinople in 381, the third at Ephesus in 431, and the fourth in 451 at Chalcedon, in the Asian suburbs of the capital, the principal business at all of these synods being doctrinal matters, particularly concerning the nature of Christ. The bishops at Chalcedon formulated what became the orthodox Christological doctrine, i.e., that Christ was both human and divine, his two natures being perfect and indivisible though separate. At the same time they condemned as heretics those who thought differently, the Monophysites, whose believers, principally in south-eastern Asia Minor, Syria, Mesopotamia, Persia and Egypt, then formed their own schismatic churches.

Many of the early translations were done by the schismatic Christians in south-eastern Anatolia, Syria, Mesopotamia and Persia, who spoke Syriac, a Semitic language deriving from Aramaic. The Syriac-speaking Christians were members of the Nestorian, Jacobite and other eastern churches, which had split with the Greek Orthodox patriarchate in Constantinople on doctrinal matters. These eastern Christians had assimilated secular Greek learning through their monasteries and schools, most notably those of the Nestorians at Edessa (Turkish Urfa) and Nisibis (Turkish Nusaybin) in northern Mesopotamia. Among the books used at these schools were Greek treatises translated into Syriac, most notably the logical works of Aristotle.

The school at Edessa, founded in the mid-fourth century AD, was the centre of higher theological studies among the Syriac-speaking eastern Christians. During the following century the scholars at Edessa were followers of Nestorius, patriarch of Constantinople (r. 429–31), whose Christological doctrines were condemned as heretical in 431 by the Council of Ephesus. This led the emperor Zeno to close the school at Edessa in 489, whereupon the Nestorian scholars moved eastward to Nisibis, which was then in Persian territory.

The eastward migration of Nestorians eventually brought them to the Sasanid capital at Jundishapur in western Persia, where in the late fifth century they joined the faculty of a medical school that had been founded by King Shapur I (r. 241–72). There the Nestorian faculty taught Greek philosophy, medicine and science in Syriac translations.

Modern historians consider the sixth century to be a watershed in the history of the empire, which from that time on they tend to call Byzantine rather than Roman, though it is usually the transfer from Nikomedia to Constantinople in 324 that signalled the beginning of the split. As the great churchman Gennadius was to say in the mid-fifteenth century, in the last days of the Byzantine Empire: 'Though I am a Hellene by speech yet I would never say that I was a Hellene, for I do not believe as Hellenes believed. I should like to take my name from my faith, and if anyone asks me what I am I answer, "A Christian." Though my father dwelt in Thessaly I do not call myself a Thessalian, but a Byzantine, for I am of Byzantium.'

The peak of the Byzantine Empire came under Justinian I (r. 527–65), who reconquered many of the lost dominions of the empire, so that the Mediterranean once again became a Roman sea. Justinian also broke the last direct link with the classical past when in 529 he issued an edict forbidding pagans to teach. As a result the ancient Platonic Academy in Athens was closed, ending an existence of more than nine centuries, as its teachers went into retirement or exile.

Those who went into exile included Damascius, the last director of the Academy, along with Isidorus of Miletus, who had been his predecessor, and Simplicius of Cilicia. They and three other scholars from the Academy were given refuge in 531 by the Persian king Chosroes I (r. 531–79), who appointed them to the faculty of the medical school at Jundishapur. The following year the six of them were allowed to come back from their exile, five of them returning to Athens, while Isidorus took up residence in Constantinople.

Justinian appointed Isidorus to be chief of the imperial architects, along with Anthemius of Tralles, their task being to design and build the great church of Haghia Sophia in Constantinople, whose foundation was laid in 532. Anthemius died during the first year of construction, but Isidorus carried the work through to completion, after which Justinian dedicated the church on 26 December 537. Haghia Sophia, which some consider to be the greatest building in the world, still stands today, a symbol of the golden age of the Byzantine Empire under Justinian.

Isidorus and Anthemius had studied and taught the works of Archimedes and the Archimedean commentaries of Eutocius of Ascalon. Isidorus was apparently responsible for the first collected edition of at least the three Archimedean works commented upon by Eutocius – *On the*

Sphere and Cyclinder, *On the Measurement of the Circle* and *On the Equilibrium of Planes* – as well as the commentaries themselves.

Isidorus of Miletus was the last physicist of antiquity, for by his time the ancient Graeco-Roman world had vanished, supplanted by the new order represented by the Christian Byzantine Empire. Byzantium would soon begin its long struggle with invaders from both West and East, the latter including the triumphant armies of Islam, leaving many of the other great cities of the Greek world in ruins. The long night of the Dark Ages had begun, and for the few who could remember the classical past it would have seemed that Greek philosophy and science had come to an end, with the famous schools of Athens closed and the Museum and Library of Alexandria destroyed, the last philosophers and scientists passing away without successors to perpetuate the ideas that had been given wing by the first physicists in Miletus more than a thousand years before.

Despite Justinian's closure of the Platonic Academy, classical Greek culture survived in Byzantium, not only in Constantinople but also in the south-eastern provinces of the empire, particularly among the schismatic Christians, who had translated Greek works into Syriac.

The best of the early Syriac translators was Sergius of Reshaina (d. 536), a Monophysite priest and physician who had been educated in the Platonic school of Ammonius in Alexandria His translations from Greek into Syriac included some of Aristotle's logical works, which were at about the same time being rendered from Greek into Latin by Boethius. He also wrote two works of his own on astronomy, *On the Influence of the Moon* and *The Movement of the Sun*, both undoubtedly based on Greek sources. Sergius was characterised by a later Syriac writer as 'a man eloquent and greatly skilled in the books of the Greeks and Syrians and a most learned physician of men's bodies. He was orthodox in his opinions... but his morals [were] corrupt, depraved and stained with lust and avarice.'

During the reign of Khosrow I there was a distinguished scholar in the court known as Paul the Persian, who is said by the later Christian philosopher Bar Hebraeus to have written an 'admirable introduction to the dialectics (of Aristotle)'. It is generally agreed that this is identical to the *Treatise on the Logic of Aristotle the Philosopher Addressed to King Kosrow*, which is extant in a Syriac manuscript in the British Museum. The *Treatise* contains an introduction to philosophy in general, an introduction to Aristotle's logical works and summaries of the individual books of the Organon studied in the Syrian tradition. Paul translated the last five books of the *Organon* into Syriac, which were later rendered into Arabic, making him an important link connecting the last Alexandrian scholars with the first philosophers who would emerge in the Islamic world. Khosrow sponsored the publication in Pahlavi of the *Royal Astronomical Tables*, apparently based on Indian and Greek sources, which would subsequently be used in the first Islamic writings on astrology and astronomy. (Ptolemy's *Almagest* had been translated into Pahlavi in the third century, and was later translated into Arabic, first by al-Hajjaj ibn Matar.)

Three Indian astronomical works of the early medieval period are referred to by al-Biruni, though we do not know whether these works were translation into Arabic or whether the early Abbasid astrologers used a Pahlavi version. The earliest of these, the *Aryabhatiya*, was written in 499 by Aryabhata; the second is the *Khandakhadyaka* of Brahmagupta, dated 665; the third is the *Zij al-Sindhind* (a *zij* is an astronomical handbook with tables), from the end of the seventh century or the beginning of the eighth. According to Regis Morelon, 'These texts are based on the yearly cycles corresponding to the Indian cosmology, and their scientific tradition is linked with an earlier period of Hellenistic astronomy than that of Ptolemy; they thus preserve a certain number of elements that can be traced back to the time of Hipparchus.'

The *Aryabhatiya* and *Khandakhadyaka* are works of mathematical astronomy. The principal contribution made by Aryabhata is his introduction of place-value notation, a version of a system first used in ancient Babylonia. Brahmagupta's greatest contribution were in algebra, particularly in indeterminate analysis, where he extended the work of Diophantus.

A distinguished Syriac scholar of the early medieval period was Severus Sebokht (d. 667), a Nestorian bishop who wrote on both scientific and theological subjects. His scientific writings included works on logic (now mostly fragments), a commentary on *peri hermeneias* by Paul the Persian, and treatises on astronomy and the astrolabe. He was also one of the first Syriac scholars to use the so-called Hindu-Arabic number system. Writing in 662, he praises the Hindus and 'their valuable methods of calculation, and their computation that surpasses description'. He goes on to say that 'I only wish to say that this computation is done by means of nine signs.'

The Islamic calendar begins in 622, though the Islamic faith is generally regarded to have begun in 610, when the Prophet Muhammed started to receive revelations from God. Arab armies under his successors, the first caliphs, conquered all of the Arabian peninsula in 634, Syria in 637, Egypt in 639, Persia in 640, Tripolitania in 647 and the Maghrib, or north-west Africa, in 670. An Arab fleet besieged Constantinople in the years 670–4 but failed to capture the Byzantine capital. During the next half-century Muslim armies conquered Transoxiana and the Sind, extending their dominion into Central Asia and the borders of India, while in the West they conquered much of Spain, known in Arabic as al-Andalus, invading France before they were stopped at Tours in 732 by Charles Martel, though skirmishes continued in the region. Resistance in Iran continued well into the ninth century, and Egypt was only conquered much later.

Mu'awiya became caliph at Jerusalem in 661 and that same year moved his headquarters to Damascus, beginning the Umayyad dynasty. The Umayyad caliphate lasted until 750, when the last of the dynasty, Marwan II, was defeated and killed by the forces of Abu'l-'Abbas al-Saffah, who had been proclaimed caliph the previous year. Thus began the 'Abbasid dynasty, which would last for more than five centuries. Abu'l-'Abbas was succeeded in 754 by his brother Abu-Ja'far al-Mansur, who in the years 762–5 built Baghdad as his new capital, beginning what would prove to be a great period in the intellectual history of Islam.

Baghdad reached its peak as a cultural centre under al-Mansur (r. 754–75) and four generations of his successors, most notably Harun al-Rashid (r. 786–809) and 'Abd-Allah al-Ma'mun (r. 813–33). According to the historian al-Masudi (d. 956), al-Mansur initiated a programme to have philosophical and scientific works in Greek and other foreign languages translated into Arabic, including 'books by Aristotle on logic and other subjects, the *Almagest* by Ptolemy, the *Arithmetic* [by Nicomachus of Gerasa], the book by Euclid [the *Elements*], and other ancient books from classical Greek, Byzantine Greek, Pahlavi, Neopersian and Syriac. These were published among the people, who examined them and devoted themselves to knowing them.'

The translation movement had actually begun in the time of the Ummayad caliphate, when some Greek medical works were translated from Syriac to Arabic, mostly by Nestorian and Jacobite Christians as well as Jews. As Dimitri Gutas has pointed out, there were also translations from Greek into Pahlavi, the middle Persian of the Sasanian dynasty, 'motivated by the belief that all learning ultimately derived from the *Avista*, the Zoroastrian canonical scriptures'. Thus they felt that Greek science had originated in Persia, and that in translating the works of Aristotle, Euclid, Ptolemy and others they were reclaiming elements of ancient Persian culture.

The historian al-Masudi writes of al-Mansur's preoccupation with astrology, which led him to employ several astrologers in his court. 'He had in his retinue Nawbakht the Zoroastrian, who converted to Islam upon his instigation ... Also in his retinue were the astrologer Ibrahim al-Fazari, the author of an ode to the stars and other astrological and astronomical works, and the astrologer 'Ali ibn Isa the Astrolabist.'

Nawbakht the Zoroastrian (d. ca. 777) was a Persian astrologer whose examination of the celestial signs had led him to advise al-Mansur to begin the construction of Baghdad on 30 July 762. His only known work is an astrological treatise called *The Book of Predictions.*

Ibrahim al-Fazari (d. ca. 777) was the first court astrologer of the ‘Abbasid caliphs. He is credited with being the first Arabic astronomer to construct an astrolabe, the subject of three of his known works. He also worked on problems of calendar reform, which he discusses in an extant poem on the Syrian months. He writes of the determination of time in another extant poem, *On the Science of Stars.*

Ibrahim al-Fazari’s son Muhammad was an astrologer in the court of al-Mansur, who ordered him to translate the Sanscrit astronomical work known as the *siddhanta*, of which there are many titles: *surya siddhanta*, *panea siddhanta*, *paulisha siddhanta*, to name a few. In Arabic they were called the *Sindhind.* According to David Pingree, the Sanskrit manuscript was given to al-Mansur by an Indian scholar who accompanied an embassy from the Sind to Baghdad in 771 or 773. Ibrahim al-Fazari used this and other sources to compile his own set of astronomical handbooks with tables, the *Zij al-Sindhind al-kabir*, in which, as Pingree notes, ‘he mingled elements from Indian, Pahlavi, and Greek sources into a usable but internally contradictory set of rules and tables for astronomical computations.’ Dimitri Gutas writes that Ibrahim al-Fazari’s translation, together with his own version of the *Sindhind*, combined with other factors to produce ‘over the centuries the spectacular tradition of Arabic astronomy’.

Ibrahim al-Fazari’s translation has not survived, but it may have been used as a source by al-Khwarizmi in his version of the *Sindhind*, which has itself survived only in a modified Latin translation. As George Saliba has pointed out regarding al-Khwarizmi’s *Sindhind*: ‘That his text survived only in a Latin version, and that the others have been all but totally obliterated, clearly indicates the quick neglect of the Indo-Persian tradition.’

‘Ali ibn Isa the Astrolabist was from Harran in northern Mesopotamia, and probably learned astronomy and astrology from ancient Babylonian sources that were still used by the local people, the Sabeans. Despite the fact that ‘Ali ibn Isa was employed as an astrologer, he wrote a *Treatise on Refutation of the Art of Predictions of Stars*, the earliest known Islamic work rejecting the notion of astrological prognostication. He was also a physician, noted for his *Treasury for Opthalmologists*, the first important Islamic treatise on the structure and illnesses of the eye, translated into Latin as *Tractus de oculis Jesu ben Hali.* ‘Ali ibn Isa is credited with being the first physician to suggest the use of anesthesia in surgery.

Nawbakht was succeeded as court astrologer by his son Abu Sahl al-Fadl ibn Nawbakht (d. ca. 815), who was possibly also chief librarian of Harun al-Rashid. Abu Sahl translated works from Persian into Arabic for the caliph, and he also wrote a number of treatises on astrology, most notably *Kitab al-Nahmutan*. This is the first book in Arabic on astrological history, a dynastic chronicle in terms of cyclical periods of varying lengths governed by the celestial bodies. He writes that 'The people of every age acquire fresh experience and have knowledge renewed for them in accordance with the decree of the stars and the signs of the zodiac, a decree which is in charge of governing time by the command of God Almighty.' Abu Sahl's motive was to show that the 'Abbasid succession was preordained by the stars and God, and that it was now their dynasty's turn to renew knowledge.

Two of Nawbakht's grandsons, al-Hasan ibn Sahl ibn Nawbakht and 'Abdullah ibn Sahl ibn Nawbakht, served as astrologers at the court of Caliph al-Wathiq, a grandson of Harun al-Rashid. Al-Hasan wrote a treatise on astronomy and also made translations from Persian into Arabic.

Theophilus of Edessa (695–789), known in Arabic as Thiyufil ibn Thuma, was a Nestorian Christian who was court astrologer and military advisor of Caliph al-Mahdi (r. 775–85). He called astrology the 'mistress of all sciences', because of the importance of astrological history under the 'Abbasids and the commissioning of horoscopes by the caliphs. He did translations of astronomical works from Greek into Syriac and also wrote a book on military astrology. Fragments of additional works in Arabic and Greek still exist.

An associate or student of Theophilus named Stephanus the Philosopher also served as astrologer at al-Mahdi's court. Stephanus visited Constantinople in the 790s, during the reign of Constantine VI (r. 780–97), when he wrote a treatise in praise of astrology. He writes in his treatise that he found nothing of the astronomical and astrological sciences in the Byzantine capital, and thus he took it upon himself 'to renew this useful science among the Romans and to implant it among the Christians so that they might be deprived of it nevermore'. According to Dimitri Gutas, 'Stephanus brought with him to Constantinople from Baghdad not only news of scientific developments there but also concrete mathematical and astrological information: an astrological technique described in a work by Theophilus was used by Pancratius, the astrologer of Constantine VI, to cast a horoscope.'

Gutas goes on to suggest that this visit by Stephanus sparked a revival of Byzantine interest in the mathematical sciences, when, 'after a hiatus of apparently over one hundred and fifty years, Greek secular manuscripts began to be copied again around 800.' He gives a list of twenty-nine ancient Greek works of science and philosophy copied in Constantinople in the years 800–50, all of which were translated into Arabic, including books by Aristotle, Euclid, Aristarchus and Ptolemy, namely his *Almagest.* Gutas suggests that this surge of copying was a direct response to the translation movement then underway in Baghdad, as well 'as an expression of the awareness by Byzantine intellectuals of the scientific superiority of Arabic scholarship and the wish to emulate it'.

One of the most distinguished astronomers in Baghdad during the early 'Abbasid period was Habash al-Hasib. Habash was born in Merv, in what is now Turkmenistan, and worked in Baghdad during the reigns of caliphs al-Ma'mun and Abu-Ishaq al-Mu'tasim (r. 833–42). He is credited with sixteen works on astronomy and three on mathematics. His best known work is *The Damascene Tables*, a revision of Ptolemy's *Almagest* in which he introduces the trigonometric functions of sine, cosine and tangent in place of the chords used by the Greeks. Habash modified Ptolemy's tables for the motions of the sun, moon and planets based on his own calculations, which were used by many later Arabic astronomers.

Another renowned astronomer of the early 'Abbasid period is Ahmad al-Farghani, whose *nisba* (our equivalent of a last name) comes from his birthplace in Transoxania. Al-Farghani worked in Baghdad during the caliphates of al-Ma'mun, al-Mu'tasim, al-Wathiq (r. 842–47) and al-Mutawakkil (r. 847–61). He is credited with eight works on astronomy, the best known of which is the *Kitab fi usul 'ilm al-nujum* – the *Book on the Elements of the Science of the Stars* – a comprehensive account of Ptolemaic astronomy in descriptive rather than mathematical terms. The *Elements* was translated into Latin in the twelfth century by both John of Seville and Gerard of Cremona, whose translation was used by Dante for the astronomical knowledge used in the *Vita nuova* and in the *Convivio.*

Ptolemy's *Tetrabiblos*, the foremost astrological work of antiquity, was translated from Greek to Arabic by the Christian scholar al-Bitriq during the reign of al-Mansur and another Arabic translation was made in the ninth century by Ibrahim al-Salt.

The most prominent astrologer in the early 'Abbasid period was Masha'allah, a Jew from Basra who was one of those whose examinations of the celestial signs led to the founding of Baghdad. His horoscopes can be dated to the period 762–809, and he served as astrologer to all of the caliphs from al-Mansur to al-Ma'mun. He wrote on every aspect of astrology, most notably an astrological history called the *Book of Mysteries*, the principal source of information about the Royal Astronomical tables sponsored by Chosroes I. He is credited with twenty-eight books, of which twenty-three have survived. Many of his works were translated into Latin; one was used by Chaucer in his famous treatise on the astrolabe, and he is referred to by Copernicus.

Alchemy was another field in which the 'Abbasids felt that there was a need for ancient Greek texts to be translated into Arabic. The geographer Ibn-al Faqih al Hamadani quotes a report by al-Mansur's secretary, 'Umara ibn Hamza, who spent some time in Constantinople during the reign of Constantine V (r. 741–75). When 'Umara returned to Baghdad he reported that he had seen the emperor transmute lead and copper to silver and gold using a dry powder he called *al-eksir*, or elixir, and 'This was the reason that induced him [al-Mansur] to become interested in alchemy.'

Jabir ibn Hayyan (ca. 721–ca. 815), known in Latin as Geber, is the supposed author of an enormous number of alchemical and other writings. The Jabirian corpus, which appears to be the work of many scholars writing somewhat later than Jabir's reputed lifetime, represents virtually all that is known of the alchemy in Islam during the early 'Abbasid period.

One basic concept of Islamic alchemy that had been inherited from the ancient Greeks was the notion that materials like sulfur and mercury could be transmuted into silver and gold. One of the works in the Jabirian corpus proposed a theory in which six metals – tin, lead, iron, copper, silver and gold – were made up of different combinations of sulfur and mercury, and could thus be transformed by adjusting the proportions of the two basic constituents before melting them and mixing them together. Aside from the theory and mystical philosophy behind it, the practice of alchemy demanded a detailed knowledge of the physical properties of the materials involved, and the processes to which they were subjected represent the beginning of chemistry.

Another work in the Jabirian corpus gives the earliest description of the flammability of alcohol, where the author writes that 'And fire which burns on the mouths of bottles [due to]... boiled wine and salt, and similar things with nice characteristics which are thought to be of little use, these are of great significance in these sciences.' Thenceforth this property of alcohol appears in alchemical and military treatises, along with the first designs for a portable alcohol lighter.

The Jabirian corpus also includes works on philosophy, astronomy, physics, mathematics and medicine. Among the best known are *The Book of Seventy*, a collection of seventy treatises on alchemy, most of which were translated into Latin, and *The Book of the Balance*, which presents the philosophical basis of Jabirian alchemy.

Islamic alchemy also involved astrology, astral cosmology, magic and other occult sciences. These branches of learning came under the heading of the 'hidden' (*khafiyyah*) sciences, in contrast to the manifest (*jaliyyah*) sciences such as mathematics.

Al-Mansur suffered from dyspepsia, or chronic indigestion, and soon after he moved into his new capital he sought the aid of the physicians at the Jundishapur medical school. His ailment was cured by the director of the hospital, Gurgis ibn Buhtisu, a Nestorian Christian, who came to Baghdad to serve as al-Mansur's personal physician. The Buhtisus became the leading practitioners of medicine in Baghdad, several generations of them serving as personal physicians to the caliphs. The historian Ibn Abi-Usaybi'a reports that al-Mansur commissioned many translations of Greek works from Gurgis ibn Buhtisu. The translations would have been done from Syriac by Nestorian scholars from Jundishapur, whose medical centre was eventually transferred to Baghdad, becoming the first hospital and school of medicine in the 'Abbasid capital.

The translation movement was also fostered by the Barmakids, a family who held the most important ministerial positions in the early years of the 'Abbasid dynasty, retaining power from 750 until 803. Harun al-Rashid's vizier, Yahya the Barmakid, one of the principal supporters of the translation programme, was from the caravan city of Marw (Merv), capital of Khurasan, the north-eastern province of Persia (now in Turkmenistan). DeLacy O'Leary notes that at the time Marw was 'one of the centres of Greek scholarship.' According to O'Leary 'From Marw came some of the earliest translators of astronomical record, and it would seem that Khurasan was the channel through which astronomical and mathematical material came to Baghdad.' He goes on to say that 'Some of the astronomical and mathematical material seems to have been obtained from India, derived from a Greek source in the first place, but probably it was transmitted to the Arabs through a Persian medium, though the actual Persian works whereby it was transmitted are no longer extant.'

Another motivation in beginning the translation programme stemmed from its role in educating the secretaries needed to administer the 'Abbasid empire. Ibn Qutayba (d. 889), in his *Adab al-Katib* (*Education of the Secretary*), enumerates the subjects that a state secretary should learn in order to be qualified for his position, disciplines whose sources were mostly in Greek. The subjects that he mentions include irrigation, surveying, architecture, technology, instrument-making, accounting, geometry and astronomy, the latter in order to measure 'the varying lengths of days, the rising-points of stars, and the phases of the moon and its influence'.

Yahya is credited by the tenth-century Tunisian scholar 'Abdallah ibn Abi Zayd with initiating the 'Abbasid policy of reviving Greek science in Islam, importing Greek books from the Byzantine Empire, and having them translated into Arabic. The translation programme continued under al-Mansur's son and successor Muhammad al-Mahdi (r. 775–85). Al-Mahdi commissioned the translation of Aristotle's *Topics* into Arabic from Syriac, into which it had been translated from Greek. Later the work was translated directly from Greek into Arabic. The motivation for translating the *Topics* was that it taught the art of systematic argumentation, which was vital in discourse between Muslim scholars and those of other faiths and in converting non-believers to Islam, which became state policy under the 'Abbasids.

Ja'far ibn Muhammad Abu Ma'shar al-Balkhi was a famous astrologer of the 'Abbasid period. It was Abu Ma'shar who put astrology on the foundation of peripatetic philosophy, one of the reasons for his importance. His *nisba* comes from his origin at Balkh in Khurasan (now in Afghanistan), where he was born on 10 August 787. David Pingree describes the rich mixture of peoples and cultures in Balkh at that time.

> The ancient city of Balkh, where Abu Ma'shar grew up, had once been an outpost of Hellenism in central Asia, and then had become a center for the mingling of Indians, Chinese, Scythians and Greco-Syrians with Iranians during the Sassanian period ...; its religious communities included Jews, Nestorians, Manichaeans, Buddhists and Hindus, as well as Zoroastrians. In the revolution of the middle of the eighth century, the people of Khurasan provided the Abbasids with their army, their general, and many of their intellectuals.

Like other intellectuals from Balkh, Abu Ma'shar – an expert in the *hadith*, or sayings of the Prophet – gravitated to Baghdad, probably at the beginning of the caliphate of al-Ma'mun. Then in 825, at the challenge of the great philosopher al-Kindi, Abu Ma'shar began studying mathematics, astronomy and astrology in order to understand philosophy. As David Pingree puts it, 'In this effort he drew upon elements of the diverse intellectual traditions to which he was almost uniquely heir: upon the Pahlavi Greco-Indo-Iranian tradition in astrology, astronomy, and theurgy...'

Abu Ma'shar's *Zij al-hazarat* was, according to Pingree, an attempt 'to restore to mankind the true astronomy of the prophetic age', which he sought to do by using Indian writings on the mean motions of the planets. Pingree gives this assessment of this and the many other works of Abu Ma'shar, who lived to be 99 years of age, or 102 according to the Islamic calendar.

> In these writings ... Abu Ma'shar did not display any startling powers of innovation. They are practical manuals intended for the instruction and training of astrologers. As such they exercised a profound effect on Muslim

> intellectual and social history and, through translation, on the intellectual and social history of western Europe and of Byzantium. Abu Ma'shar's folly as a scientist has been justly pointed out by al-Biruni .... He is an interesting and instructive phenomenon, but is not to be ranked among the great scientists of Islam.

And thus science and philosophy came to Baghdad by many roads, ranging from Athens, Alexandria and Constantinople in the West to Khurasan in Central Asia and India in the East, drawn by the brilliance of the ‘Abbasid capital. Baghdad reached its prime during the reign of Harun al-Rashid, whose accession is described in the *Thousand and One Nights.*

> And Harun, amid the pomp of his kingship, received oaths of obedience from the emirs, the notables and all the assembled people .... And all the provinces and lands of the Empire, and all the Islamic peoples, Arab and non-Arab, Turks and Daylamites, hailed the authority of the new Khalif and swore allegiance to him. And he began his reign in prosperity and magnificence, and sat shining in his new glory and in his power.

CHAPTER 4

‘Abbasid Baghdad: The House of Wisdom

The translation programme in Baghdad under the early ‘Abbasids was centred at the famous *Bayt al-Hikma*, or House of Wisdom, which originally seems to have been basically a library and remained so. Pahlavi manuscripts were kept there and in the early ‘Abbasid period some of these were translated into Arabic. The principal source for the works used and produced by the translators is Abu’l-Faraj Muhammad ibn al-Nadim, whose father was a Baghdad bookseller and who in 987–8 produced a catalogue of the books that were available in the city at that time. Ibn al-Nadim notes that the court astrologer Abu Sahl ibn Nawbakht was employed by Harun al-Rashid at the *Bayt al-Hikma*, where ‘he translated from Persian into Arabic and relied in his scholarship on the books of Iran ...’

Dimitri Gutas writes of the *Bayt al-Hikma* that ‘It was a library, most likely established as a “bureau” under al-Mansur, part of the ‘Abbasid administration modeled on that of the Sasanians. Its primary function was to house the activity and the results of translations from Persian into Arabic of Sasanian history and culture. As such there were hired translators capable to perform this function as well as book binders for the preservation of books.’ He notes that ‘Under al-Ma’mun it seemed to have gained an additional function related to astronomical and mathematical activities ... We have, however, no specific information about what these activities actually were; one would guess research and study only, since none of the people mentioned was himself actually a translator.’

Gutas goes on to say that the *Bayt al-Hikma* ‘was certainly not a center for the translation of Greek works into Arabic ... Among the dozens of reports about the translation of Greek works into Arabic that we have, there is not even a single one that mentions the *bayt al-hikma*.' Neither was it 'an "academy" for teaching the "ancient" sciences as they were being translated,' he says, nor 'a "conference" center for the meeting of scholars'. Despite these caveats, from the number of famous translators who were associated with the *Bayt al-Hikma* it would appear that translations were in fact done there.

It is possible that Aristotle's *Physics* was first translated into Arabic during the reign of Harun al-Rashid, the motivation apparently being its use in theological disputations concerning cosmology. Although al-Masudi says that Euclid was translated during the reign of al-Mansur, it would appear that the earliest translation of the *Elements* was done during Harun al-Rashid's reign by the mathematician al-Hajjaj ibn Matar (fl. c. 786–833), under the patronage of the vizier Yahya ibn Khalid ibn Barmak.

Harun al-Rashid's son al-Ma'mun continued the translation programme of his father. Several Muslim and Christian scholars tell the story of how Aristotle appeared to al-Ma'mun in a dream, a legend that was probably concocted, as Dimitri Gutas suggests, to promote 'caliphal authority at the expense of religious law'. One version of the dream, which became the founding legend of the translation movement, is recounted by Yahya bin 'Adi:

> Al-Ma'mun dreamed that he saw a man of reddish-white complexion with a high forehead, bushy eyebrows, bald head, dark blue eyes and handsome features, sitting on his chair. Al-Ma'mun said: 'I saw in my dream that I was standing in front of him, filled with awe. I asked, "Who are you?" He replied, "I am Aristotle." I was delighted to be with him and asked, "O philosopher, may I ask you some questions?" He replied, "Ask." I said, "What is the good?" He replied, "What is good according to the intellect." I asked, "Then what?" He replied, "Whatever is good according to religious law." I asked, "Then what?" He replied, "Whatever is good according to the masses." I asked, "Then what?" And he replied, "There is no more then."'

During the reign of al-Ma'mun some mathematicians and astronomers were associated with the *Bayt al-Hikma*. One of them was al-Hajjaj ibn Matar, who was said by Ibn al-Nadim to have made a second translation of Euclid's *Elements* for al-Ma'mun, though other Arabic sources claim differently. Ibn al-Nadim reports that the famous astronomer Muhammad ibn Musa al-Khwarizmi (fl. ca. 828) 'was employed full-time in the *Bayt al-Hikma* in the service of al-Ma'mun'.

Al-Khwarizmi is renowned for his treatise *Hisab al-jabr wa al-muqabala*, known more simply as *Algebra*, written ca. 825. In his preface he writes that Caliph al-Ma'mun 'encouraged me to compose a compendious work on algebra, confining it to the fine and important parts of its calculation, such as people constantly require in cases of inheritance, legacies, partition, law-suits and trade, and in all their dealings with one another, or where surveying, the digging of canals, geometrical computation, and other objects of various sorts and kinds are concerned'.

Abu-Kamil Shoja ibn Aslam, an Arabic writer on mathematics, notes that 'The first thing which is necessary for students in this science [algebra] is to understand the three species which are noted by Muhammad ibn Musa al-Khwarizmi in his book. These are roots, squares and numbers.' Al-Khwarizmi distinguished six types of problems involving linear and quadratic equations with positive numbers as solutions. After solving these problems numerically in the first five chapters of his book, he tells us in the introduction to the sixth chapter that he will now demonstrate them geometrically: 'We have said enough so far as numbers are concerned, about the six types of equations. Now, however, it is necessary that we should demonstrate geometrically the truth of the same problems which we have explained in numbers.'

The Turkish historian of science Aydın Sayılı suggests that an Islamic mathematician named 'Abd-al-Hamid ibn Turk al-Khuttali, working in Baghdad in the first half of the ninth century, may have independently worked along similar lines to al-Khwarizmi in the development of algebra, and he raises the possibility that both of them derived their ideas from an earlier source. According to O'Leary: 'It may be that mathematics and astronomy came through Indian authorities, not translations from the Greek but based upon Greek teaching, and translations from Greek into Syriac and Arabic came later when efforts were made to check and correct the available material.' He goes on to say that 'Certainly the earliest Arab mathematicians, such as al-Khwarizmi, knew a great deal which does not appear in the Greek authors and much of which (but not all) can be traced to Indian workers.'

Following its presence in al-Andalus and elsewhere in Muslim Europe and its use by Muslim scholars, al-Khwarizmi's *Algebra* was first translated into Latin by Robert of Chester in 1145, and thus we can see – in a very simplified way – the advancement and spread of disciplines such as algebra through the men who studied such treatises and the cultures that fostered them.

Another of al-Khwarizmi's mathematical works survives only in a unique copy of a Latin translation entitled *De numero indorum* (*Concerning the Hindu Art of Reckoning*). This is the title given to the work in the nineteenth century. The Arabic title was different but no one can be sure of its exact wording and the Arabic version has been lost. This work, which is probably based on Brahmagupta’s *Khandakhadyaka*, describes the Hindu numerals that eventually became the digits used in the modern western world. The new notation came to be known as that of al-Khwarizmi, corrupted to ‘algorism’ or ‘algorithm’, which now means a procedure for solving a mathematical problem in a finite number of steps that often involves repetition of an operation. *De numero indorum* explains the use of the Hindu numerals in the four basic operations of addition, subtraction, multiplication and division, dealing with both common and sexagesimal fractions and extracting the square root.

Al-Khwarizmi is the author of the earliest extant original work of Islamic astronomy, the *Zij al-Sindhind*, based on an Indian work. The *Sindhind* was most likely used for centuries in the Islamic world and was subsequently updated and revised in al-Andalus by the Arabic astronomer al-Majriti. Al-Majriti’s revision of the *Sindhind* was translated into Latin early in the twelfth century by Adelard of Bath and was widely used in Europe. Only the Latin translation now survives, the original Arabic work having fallen into disuse in the Islamic world after the twelfth century.

Al-Khwarizmi also wrote the first comprehensive treatise on geography, the *Kitab ṣurat al-ard*, or *Book of the Form of the Earth*. This consists entirely of the latitudes and longitudes of cities and other places, arranged in seven sections according to the *climata* or ‘climates’ of Ptolemy and other Greek geographers. It has been suggested that al-Khwarizmi’s *Form of the Earth* is based on an earlier work commissioned by Caliph al-Ma’mun, which was itself derived from Ptolemy’s *Geography*.

Another extant work of al-Khwarizmi is a short treatise on the Jewish calendar as well as two treatises on the astrolabe and a chronicle of Islamic history.

Important figures in the programme for sponsoring science under al-Ma’mun and his immediate successors were the Banu Musa, three brothers named Muhammed, Ahmad and al-Hasan. These were the sons of Musa ibn Shakir, a former highway robber who became an astrologer in Merv, where he befriended al-Ma’mun before the latter became caliph in 813. When Musa died his three sons were taken into the care of al-Ma’mun, who had them educated in Baghdad after he became caliph. After finishing their studies the Banu Musa served al-Ma’mun and his immediate successors in various ways, becoming rich and powerful in the process. They spent much of their wealth in collecting ancient manuscripts, and they also supported a group of translators in Baghdad.

The Banu Musa themselves are credited with writing some twenty books on mathematics, astronomy and engineering. The most important of their mathematical works is the *Book on the Knowledge of Measuring Plane and Spherical Figures*, which was translated into Latin in the twelfth century by Gerard of Cremona. Here the Banu Musa used a technique similar to Archimedes' 'method of exhaustion' for determining the area of a circle. Their *Premises of the Book of Conics* is a recension of the *Conics* of Apollonius of Perge. They also wrote other works on mechanics and musical theory, the most important of which is *The Book of Ingenious Mechanical Devices*.

The historian Ibn Khallikan also tells the story, perhaps apocryphal, of how al-Ma'mun directed the Banu Musa to measure the circumference of the earth, to verify the size of the Greek measurement of *stadion* made by Eratosthenes and other ancient Greek scientists. The method used by the Banu Musa was to measure the north–south distance between two points in the Sinjar desert where the elevation of the pole star differed by one degree, whereupon they multiplied this by 360 to obtain the circumference of the earth. The value they obtained, according to Ibn Khallikan, was 8,000 *farsakhs*, or 24,000 miles, as compared to the presently accepted value of 24,092 miles.

Two well-known translators in Baghdad were Hunayn ibn Ishaq and Thabit ibn Qurra, both of whom were patronised by the Banu Musa 'for full-time translation', according to the philosopher Abu Sulayman al-Sigistani, who says they were paid a salary that put them on a par with the highest officials in the government bureaucracy.

Hunayn ibn Ishaq (808–73), known in Latin as Joannitus, was born at al-Hira in southern Iraq, the son of a Nestorian apothecary. According to Hunayn's autobiography, he went to Baghdad to study under the Nestorian physician Yuhanna ibn Masawayh (d. 857), personal physician to al-Ma'mun and his successors. But his frequent questions annoyed Ibn Masawayh, who dismissed him and said he was wasting his time studying medicine, when he could be peddling counterfeit coins along the roadway like his compatriots from Hira:

> What makes the people of Hira want to study medicine? Go away and find one of your friends; he will lend you fifty *dirhems*. Buy some little baskets for a *dirhem*, some arsenic for three *dirhems*, and with the rest buy coins of Kufa and of Qadisiyya. Coat the money of Qadisiyya with arsenic and put in the baskets and stand by the side of the road crying: 'Here is true money, good for giving alms and for spending.' Sell the coins; that will earn you much more than studying medicine.

Hunayn, who at the time knew only Syriac, then went away to 'the land of the Greeks' until he became proficient in Greek, after which he lived in Basra for a time to learn Arabic. He then moved to Baghdad, where he soon became a member of the circle of physicians and philosophers who gathered around Caliph al-Wathiq. Al-Wathiq's successor, Caliph al-Mutawakkil, appointed Hunayn as his head physician, thus ending the monopoly of the Bukhtishu in this post. One of the Bukhtishu managed to turn al-Mutawakkil against him and Hunayn was imprisoned. But when the caliph became ill he released Hunayn and restored him as chief physician, a position he held for the rest of his days. Ibn Khallikan describes Hunayn's sybaritic life style in his latter years:

> He went to the bath every day after his ride and had water poured on him. He would then come out wrapped in a dressing gown and, after taking a cup of wine with a biscuit, lie down until he had stopped perspiring. Sometimes he would fall asleep. Then he would get up, burn perfumes to fumigate his body and have dinner brought in. This consisted of a large fattened pullet stewed in gravy with a half kilo loaf of bread. After drinking some of the gravy and eating the chicken and the bread he would fall asleep. On waking up he drank 4 *ratls* [perhaps 2 litres] of old wine. If he felt like fresh fruit, he would have some Syrian apples and quinces. This was his habit until the end of his life.

Hunayn and his students, who included his son Ishaq ibn Hunayn and his nephew Hubaish, made translations from Greek into both Syriac and Arabic. Hunayn was indefatigable in his search for Greek manuscripts, as he writes in regard to Galen's *De demonstratione*: 'I sought for it earnestly and traveled in search of it in the lands of Mesopotamia, Syria, Palestine and Egypt until I reached Alexandria, but I was not able to find anything, except about half of it at Damascus.' He was meticulous and set very high standards for his work, as he remarks in telling of his translation of Galen's *On the Best Sect*, known in Latin as *De Sectis*:

> I translated it when I was a young man ... from a very defective Greek manuscript. Later when I was forty-six years old, my pupil Hubaish asked me to correct it after having collected a certain number of Greek manuscripts. Thereupon I collated these to produce one correct manuscript and I compared this manuscript with the Syriac text and corrected it. I am in the habit of proceeding thus in all my translation work.

Hunayn writes of the translations of the writings of Galen done by him and his school in a work entitled *Hunayn ibn Ishaq's Missive to 'Ali ibn Yahya on Galen's Books Which, so far as He [Hunayn] Knows, Have Been Translated and Some of Those Books Which Have Not Been Translated.* Some of these were revisions of earlier translations, such as the one that Hunayn and his colleagues did of Sergius of Reshaina's translation into Syriac of Galen's *On* *the Method of Healing*. Hunayn, in commenting on this work, remarks that it was one of the books that was studied at the school of medicine in Hellenistic Alexandria: 'These are the books to which reading was confined at the place of teaching medicine in Alexandria, and were read in the order I have cited them. [Students] gathered every day to read and understand a principal book, in the same way as our Christian companions assemble at present at the places of teaching known as "Schools".'

Hunayn's *Missive* lists 129 of Galen's works, of which he and his colleagues translated about ninety from Greek into Syriac and the rest into Arabic. The first that he himself did, completed when he was not yet seventeen, was *On the Types of Fevers*, translating it into Syriac, which he later improved upon when he had better Greek manuscripts. Their translations also included the medical works of Hippocrates, Euclid's *Elements*, and *De Materia Medica* of Dioscorides, which became the basis for Islamic pharmacology. His son Ishaq ibn Hunayn's extant translation of Aristotle's *Physics* is the last and best version of that work in Arabic. His translations included Ptolemy's *Almagest*, while his father Hunayn revised the *Tetrabiblos*. Hunayn himself also revised an earlier translation of Galen by Yahya ibn al-Bitriq (d. 820); these were synopses that contained Plato's *Republic*, *Timaeus* and *Laws*, the first rendering of the Platonic dialogues into Arabic.

Hunayn was an outstanding physician, though his rivals complained that his medical knowledge came only through his translations. These jealous rivals made his life miserable, Hunayn complains in his treatise *On Misfortunes and Hardships Which Befell Him at the Hands of His Adversaries, Those Renowned but Wicked Physicians of His Time*, of whom he enumerates fifty-six who at one time or another were in the service of the caliphs.

Hunayn wrote two books on medicine, both extant in Arabic. One of them, *Questions on Medicine*, a history of the subject, was written in collaboration with his nephew Hubaish; the other a treatise entitled *On the Properties of Nutrition*, was based on Galen and other Greek writers. Although Hunayn did not make any original contributions to medicine, his medical writings and his translations provided the basis for the education of Arabic-speaking physicians.

Hunayn wrote on a number of other fields as well, the remarkable range of his interests evident in the titles of some of his books: including *Book on Meteors*, *Book on Colors*, *Treatise on the Comets and Miracles mentioned about Comets*, *A Greek Grammar*, *Book on Rainbows*, *Book of Questions about the Eye*, *Book on Ebbs and Flows of the Tides*, *The Truth of Religious Creeds*, *A Universal History*, *A Book on the Cause of Seawater Becoming Salty*, a *Book on Alchemy*, and a paraphrase of Aristotle's *On the Heavens*.

Thabit ibn Qurra (ca. 836–901) was born in the northern Mesopotamian city of Harran, a centre of the ancient Sabean cult, an astral religion in which the sun, moon and five planets were worshipped as divinities. Several Arabic histories tell the story of how Caliph al-Ma'mun, when he first came to Harran, was shocked to find that the people there were pagans, and he ordered them to adopt one of the recognised religions, Islam, Judaism, Christianity or Mazdeanism. They were alarmed by this and sought the aid of an authority on Islamic law, who 'advised them to claim to be Sabeans (*Sab'ia*), as those are mentioned in the Qur'an as one of the "peoples of the Book"'. O'Leary states that 'The story is obviously apocryphal,' and he explains 'how the Harranites came to be called Sabeans, a name which we now recognise as not belonging to them.'

According to Bar Hebraeus, Thabit 'was originally a money-changer in the market of Harran, and when he turned to philosophy he made wonderful progress and became expert in three languages, Greek, Syriac and Arabic... In Arabic he composed about 150 works on logic, mathematics, astronomy and medicine, and in Syriac he wrote another fifteen books.'

Thabit was 'discovered' in Harran by Muhammed ibn Musa, one of the Banu Musa brothers, who was returning from an expedition to find ancient manuscripts in the Byzantine Empire. Muhammed brought the young Thabit back with him to Baghdad, where he became one of the salaried translators who worked for the Banu Musa along with Ishaq ibn Hunayn. After Thabit established himself a number of his fellow Sabeans joined him in Baghdad, where they formed a school of mathematics, astronomy and astrology that lasted through three generations of his family.

Thabit translated writings from both Syriac and Greek into Arabic, including commentaries by Aristotle, Archimedes, Apollonius, Hero, Ptolemy, Nicomachus, Menelaus, Eutocius, Hippocrates and Galen.

Eighty manuscripts of Thabit's own works survive, including 30 in astronomy, 29 in mathematics, 4 in history, 3 in mechanics, 3 in descriptive geography, 2 in philosophy, 2 in medicine, 2 in mineralogy, 2 in music, 1 in physics and 1 in zoology. Dimitri Gutas lists seventy of his extant works, ten of which cannot be definitely verified as being by Thabit.

Thabit's original work in mathematics, physics, astronomy and medicine, as well as astrological and talismanic texts, translated from Arabic to Latin, was highly influential in the early development of European science. Roger Bacon refers to him as 'the supreme philosopher among all Christians, who has added in many respects, speculative as well as practical, to the work of Ptolemy'. But Thabit, as we know, was not a Christian, nor did he ever convert to Islam, for till the end of his days he remained a Sabean, which in Bacon's eyes would have made him a pagan or heathen, a worshipper of the celestial bodies.

Thabit's contributions in mathematics include calculating the volume of a paraboloid and giving geometrical solutions to some quadratic and cubic equations. He formulated a remarkable theorem concerning so-called 'amicable numbers', where each number of an 'amicable' pair is the sum of the proper divisors of the other, the smallest such pair being 220 and 284. His *Book on the Composition of Ratios* was important in the development of the concept of what a number was. His *Treatise on the Secant Figure* was used in spherical astronomy. He also gave a generalisation of the Pythagorean theorem that applies to all triangles, whether right or scalene, although he did not prove it. Other treatises deal with solid geometry and problems involving the conic sections and both plane and solid geometry. In two of his books he tries to prove Euclid's famous fifth postulate, which defines parallel lines, one of the earliest such attempts in the Islamic world to solve a problem that in the nineteenth century gave rise to non-Euclidean geometries.

Thabit's researches on astronomy include studies of the motion of the sun, moon and stars. In his treatise *On the Motion of the Eighth Sphere* he revived the erroneous 'trepidation theory' of Theon of Alexandria, which held that the pole of the heavens oscillated back and forth, opposed to the correct theory, first given by Hipparchus, that the celestial pole precessed in a circular path. A number of later Arabic astronomers followed Thabit's version of the theory of trepidation.

Thabit wrote an introduction or 'study-aid' to Ptolemaic astronomy and cosmology entitled *The Almagest Simplified*, (there are apparently three such texts by Thabit) which includes a commentary on Ptolemy's cosmic scale of distances in the *Planetary Hypotheses.* Thabit pictured the planets as being embedded in solid spheres with a compressible fluid between the orbs and the eccentric circles, however these concepts originate with Ptolemy. His planetary theory included a mathematical analysis of motion, in which he referred to the speed of a moving body at a particular point in space and time, the so-called instantaneous velocity, a concept that, much later and through many different permutations, became part of modern kinematics.

Thabit has also been credited with writing an astronomical treatise known as *The Book of the Solar Year*, but recent scholarship has shown that the text is possibly a revision of the one by the Banu Musa. The object of this book was to study the sun's apparent annual motion among the stars to determine the length of the tropical year, defined to be the time between two successive spring equinoxes. The author criticises Ptolemy's work in determining the length of the solar year, as he writes in conclusion: 'As well as the error of calculating the duration of the solar year from a point on the ecliptic, Ptolemy has created further error as a result of his observations themselves: he did not conduct them as they should have been conducted and it is this part of the error that has most seriously damaged the method of computation that he has proposed.'

This measurement is mentioned by Copernicus, who believed that it had been made by Thabit. The value for the sidereal year given in the *Book of the Solar Year* is 365 days, 6 hours, 9 minutes and 12 seconds, which differs from the currently accepted value by just 2 seconds. The work was apparently part of a project to rewrite the whole of Ptolemy's *Almagest*, and it contained a number of innovations which could have been adopted by later Arabic astronomers.

Thabit wrote a commentary on Aristotle's *Physics* in which he differed from the Aristotelian theory of natural place and natural motion. According to Aristotle, the four elements occupy concentric spheres, earth at the centre surrounded successively by water, air and fire, and if displaced move up or down to their natural place. Thabit suggested that it is the relative weight of the various elements that causes them to move one way or the other, earth moving downward because it is the heaviest, followed by water, with air and fire going upward because they are lighter.

Thabit also wrote paraphrases on Aristotle's *Analytica Priora* and *Hermeneutica* and *Categories and Metaphysics*, as well as, possibly, treatises on the *Nature of the Stars and Their Influences*, *Principles of Ethics* (though this cannot be confirmed as only a short fragment of such a work exists in Istanbul), *Book on Music*, *Book on Geography* (or rather, his translation of Ptolemy's *Geography*) as well as a couple of summaries of Ptolemy's *Tetrabiblos*, *Reasoning on why Seawater Became Salty*, *Book on Why the Mountains Were Created* and a *Book on Divisions of the Days of the Week According to Seven Planets* (i.e., the sun, moon and five visible planets). Another of Thabit's original works is entitled *The Nature and Influence of the Stars*, which laid out the philosophical basis of Islamic astrology. He also wrote several works on the theory and construction of sundials.

Thabit's single extant work on magic and talismans is entitled *Kitab al-hiyal* (*Book on Ingenious Manners*). This survives only in medieval Latin translations bearing the titles *De prestigious* (*On Magic*) or *De imaginibus* (*On Images*), which has been described as a 'Handbook for manufacturing metallic, wax and clay images of people, animals, cities or countries for magic operations connected with astrology.'

Thabit's four extant theological works are all concerned with the Sabeans, their history, chronology, religion and customs. One of them, a Syriac manuscript entitled *Book of Confirmation of the Faith of Hanpe*, proudly presents Thabit's claim that the Sabeans were heirs of the ancient pagan culture that civilised the world.

> We are the heirs and offspring of paganism which spread gloriously over the world. Happy is he who for the sake of paganism bears his burden without growing weary. Who has civilised the world and built its cities, but the chieftains and kings of paganism? Who made the ports and dug the canals? The glorious pagans founded all these things. It is they who discovered the art of healing souls, and they too made known the art of healing the body and filled the world with civil institutions and with wisdom which is the greatest of goods. Without them the world would be empty and plunged in poverty.

Another prominent figure of the translation movement was Qusta ibn Luqa (ca. 820–ca. 912), who was born near Heliopolis in Syria. He was a Melkite Greek Christian, who knew Syriac and Arabic. Qusta went to work in Baghdad as a physician and translator and also wrote a number of scientific works. He spent his last years as a client of King Sancherib of Armenia, where he died.

According to his Arabic biographers, Qusta was renowned as a physician and was an expert in philosophy, logic, astronomy, geometry, arithmetic and music, his translations including works of Aristarchus, Aristotle, Hero, Diophantus, Galen and Theodosius of Bithynia. His translation of Hero's *Mechanics* is the only extant text of that treatise, and his translation of the *Arithmetica* of Diophantus was vital in the survival of the work, since the last four books of Greek original are lost. His translations of Aristotle's writings include commentaries by Alexander of Aphrodisias and John Philoponus. He is credited with the translation of books xiv and xv of Euclid's *Elements*, and *De Materia Medica* of Dioscorides, as well as original treatises on medicine, astronomy, metrology and optics. His medical works include a treatise on sexual hygiene, a book on medicine for pilgrims, treatises *On Insomnia*, *On Sleep and Dreams*, *On Length and Shortness of Life*, and *On the Diversities of the Character of Men*. His treatise *On the Difference Between the Spirit and the Soul* was translated into Latin by John of Seville, and is referred to by Albertus Magnus and Roger Bacon, among others.

Qusta also wrote a work on magic entitled *Epistle concerning Incantations, Adjurations and Amulets*, a Latin translation of which is cited by Albertus Magnus. Qusta's attitude toward sorcery is evident from an anecdote in this book, where he tells the story of 'a certain great noble of our country', who believed that a witch had made him impotent. Qusta advised the noble to rub himself down with the gall of a crow mixed with sesame, persuading him that this was an aphrodisiac, and this gave the man such confidence that he overcame his imaginary ailment and regained his sexual powers.

The translation programme at the *Bayt al-Hikma* would not have been possible without the paper-mills of Baghdad, which were also the source of the profusion of manuscripts produced in the tenth century Islamic renaissance. Books became widely available and the profession of booksellers flourished; by the end of the ninth century there were more than a hundred premises in Baghdad at which books were made. There are known to have been thirty-six libraries in Baghdad when the city was sacked by the Mongols in 1258, and many private libraries as well. Works in philosophy, science, history, literature and all fields of knowledge became available to everyone who was literate. Students and scholars were drawn to Baghdad from all the lands of Islam, along with merchants, artisans and workers in every conceivable field of labour, for by the time of Harun al-Rashid the population had risen to perhaps a million, making it the largest city in the world.

The port city of Basra, founded in 650, also became a thriving metropolis, described by the geographer Yakubi as 'the world's greatest city and first centre of commerce and riches'. Its financial centre thronged with Muslim Arabs and Persians as well as Christians, Jews and Indians, with a booming industrial quarter whose sugar factories and spinning mills supplied a large part of the Islamic world, its shipyard building vessels for the port, which handled the major part of trade between Muslim countries and the Orient. Basra also became an important cultural centre, giving birth to a number of notable writers, the most celebrated being the poet Abu Nuwas, who is associated with Harun al-Rashid. As Shehrazade says in the *Thousand and One Nights*, referring to Abu Nuwas: 'For you must know that Harun al-Rashid was always wont to send for the poet when he was in an evil humour, in order to distract himself with the improvised poems and rhymed adventures of that remarkable man.'

The scholars who came to Baghdad and Basra brought with them the widest spectrum of beliefs and ideas, the mixed ingredients in the intellectual stew that came to a boil in Baghdad in the time of Harun al-Rashid and his vizier Yahya the Barmakid. The dawn of this enlightenment is commemorated in an encomium by the court poet Ibrahim al-Mosuli:

See you not how the sun grew faint
And when Harun ruled, gave again his light?
O joy that God's trustee is now Harun,
He of the generous dew, and Yahya his vizier.

CHAPTER 5

‘Spiritual Physick’

Islamic science developed apace with the translation movement, generated by polymath philosophers and scientists of extraordinary versatility. The founding of Islamic philosophy is credited to Abu Yusuf Yaqub ibn Ishaq al-Kindi (ca. 801–66), the Latin Alkindes, famous in the West as the ‘Philosopher of the Arabs’ – an epithet also given to him in both Arabic and Persian sources. Al-Kindi was from a wealthy Arab family in Kufa, in present-day Iraq, which he left to study in Baghdad. There he founded his own intellectual circle of patronage, translation, writing and teaching, enjoying the patronage of al-Ma’mun and his successor al-Mu’tasim. He was not a translator himself, knowing neither Greek nor Syriac, but he appears to have worked on the Arabic texts of those who did the translations, correcting, completing or commenting upon them. He was also a patron of the translation movement.

Al-Kindi benefited from the translation movement to become the first of the Islamic philosopher-scientists, forging a Neoplatonic reconciliation between Platonic and Aristotelian philosophy. Ibn al-Nadim listed 242 works by al-Kindi, including treatises in philosophy, astronomy, cosmology, mathematics, physics meteorology, optics, medicine, pharmacology, zoology, geography, meteorology, mineralogy, metallurgy, music, cryptology, politics, theology, alchemy and astrology, as well as technological writings on such topics as the making of clocks, astronomical instruments, and even of objects such as swords. Only about ten per cent of these works have survived and been edited.

Al-Kindi’s extraordinarily wide range of interests is characteristic of Islamic philosopher-scientists, as it had been for Aristotle, for they were interested in everything in creation. But not everything that al-Kindi wrote was of the highest quality, and some of it is no more than superstition typical of the times, such as the notion that the characteristics of various peoples are determined by the configuration of the celestial bodies above their homeland.

The longest of al-Kindi's extant works is *On First Philosophy*, of which only the first four chapters have survived. The title is Kindi's homage to ancient philosophies such as that of Aristotle, who referred to metaphysics as the 'first philosophy', which, as al-Kindi says in his introduction, is the knowledge of the causes of things: 'Knowledge of the first cause has truthfully been called "First Philosophy", since all the rest of philosophy is contained in its knowledge. The first cause is, therefore, the first in nobility, the first in genus, the first in rank with respect to that knowledge which is most certain; and the first in time, since it is the cause of time.'

Al-Kindi acknowledged his debt to the Greeks in the search for truth, writing that knowledge is accumulated across the centuries through the efforts of many scholars extending and perfecting the work of their predecessors. As he wrote in the preface to *On First Philosophy*, which he dedicated to Caliph al-Mu'tasim: 'We should not be ashamed to acknowledge truth and to assimilate it from whatever source it comes to us, even if it is brought to us by former generations and foreign peoples. For him who seeks the truth there is nothing of higher value than truth itself; it never cheapens or abases him who searches for it, but ennobles and honours him.'

Many of al-Kindi's ideas were influenced by Aristotle, as is evident from his treatise *On the Number of Books by Aristotle and What is Needed to Learn Philosophy*. But he was also influenced by the Neoplatonists Porphyry and Proclus, the Stoics, John Philoponus and other Alexandrian philosophers of the sixth century, and by the occult sciences of the *Corpus Hermeticum*. As he notes in the preface to *On First Philosophy*, he established the practice of quoting from Aristotle and other Greek writers and then commenting upon their ideas and adapting them to Islamic language: 'My principle is first to record in complete quotations all that the Ancients have said on the subject; secondly to complete what the Ancients have not fully expressed, and this according to the usage of our Arabic language, the customs of our age and our own ability.'

The world is finite in both space and time, according to al-Kindi, who believed that it had been created out of nothing by God, in which he disagreed with the Greek rejection of creation *ex nihilo*. This was due to al-Kindi's desire to reconcile Greek philosophy and Islamic theology, to create a philosophy for an Islamic community, which is evident in his work *On the Number of Aristotle's Works*, where he contrasts the approach of rational philosophers with that of prophets of revealed religion: 'The philosopher may intend to answer such questions with great effort, using his own devices, which he has at his disposal due to long perseverance in inquiry and exercise. But we will find that he does not arrive at what he seeks with anything like the brevity, clarity, unerringness, and comprehensiveness that is shown by the answer of the Prophet.'

Al-Kindi generally takes the Aristotelian view in his treatise on the *Five Essences*, which he identifies as matter, space, form, motion and time. In another treatise, the *Nature of the Sphere is Different from That of the Four Elements*, he adopts Aristotle's model in which the four terrestrial elements – earth, water, air and fire – are arranged in concentric spheres from earth outward, and says that the celestial bodies are composed of a 'fifth element', or 'quintessence', which he does not name, but that is obviously the aether of Anaxagoras and Aristotle.

Al-Kindi's treatise on the *Definitions and Descriptions of Things* follows the example of Aristotle's *Metaphysics* in defining and elaborating on the technical terms used in philosophy. This contributed to the development of the vocabulary of Islamic philosophy, although many of the terms introduced by al-Kindi were changed by later Arabic writers.

Al-Kindi was the first in Islam to classify the sciences, basing his system on the classification of Aristotle's works, beginning with the logical treatises and followed by the physical, psychological, metaphysical and ethical writings. He did not include mathematics in his system, since he considered it to be a necessary introduction to the study of philosophy rather than an integral part of the philosophical system. He emphasised this in a treatise entitled *That Philosophy Cannot be Acquired Except with a Knowledge of Mathematics.*

He was also an Islamic theorist of music, following in the Pythagorean tradition. His system was based on ancient Greek musical theory, where he used the letters of the alphabet to designate the notes of the scale, a notation that was adopted a century later in Europe.

Al-Kindi's work on optics follows Theon of Alexandria in studying the propagation of light and the formation of shadows, while his theory of the emission and transmission of light is based on that of Euclid, which is based on the erroneous idea that visual images are created by rays that are transmitted by the eye to the object observed, rather than the other way round. His ideas on visual perception, which differed from those of Aristotle, together with his studies of the reflection of light, laid the foundations for what became, in the European renaissance, the laws of perspective. Al-Kindi's two treatises on optics, *De aspecticus*, which is a manual on ancient Greek optics, and *On Burning Mirrors*, were translated into Latin in the twelfth century. *De aspecticus* was read by Robert Grosseteste and Roger Bacon, who refers to al-Kindi's concept of the velocity of light. The latter treatise represents an advance on what Anthemius of Tralles, one of the last two mathematical physicists of antiquity, had done in his work on the same subject.

One of al-Kindi's extant works is on ethics, entitled *On the Art of Dispelling Sorrows.* This is based on the Stoic concept that happiness should not be based on the transient things of the physical world, but on the universal forms of the intellectual realm. He writes that 'It is impossible for someone to attain everything he seeks, or to keep all of the things he loves safe from loss, because stability and permanence are nonexistent in the world of generation and corruption we inhabit. Necessarily, stability and permanence can only exist in the world of the intellect.'

Al-Kindi considered astrology to be a science, as he claims in a work called *The Theory of the Magic Art*, or *On Stellar Rays*, which survives only in medieval Latin manuscripts. He begins the treatise by saying that stellar rays are emitted by celestial bodies and influence everything in the universe, mankind included, and that a study of the heavens thus allows astrologers to predict the future. He concludes with a discussion of the magical power of talismanic inscriptions, an occult art that is still a popular custom among certain Islamic countries: 'The sages,' he writes, 'have proved by frequent experiments that figures and characters inscribed by the hand of man on various materials with intention and due solemnity of place and time and other circumstances have the effect of motion upon eternal objects.'

Aside from his contribution in bringing Aristotelian thought to some of the scholars of Baghdad, al-Kindi never established a school of philosophy. Some of al-Kindi's treatises were translated into Latin in the twelfth century, by Gerard of Cremona and Avendauth. He is referred to by Albertus Magnus and Giles of Rome, who in his *De erroribus philosophorum* points out al-Kindi's 'errors', particularly in cosmology and astrology.

Al-Kindi seems to have been a particularly difficult character, at least according to his contemporary al-Jahiz, who satirises him in his *Book of Misers.* As al-Jahiz tells the story, al-Kindi, despite his wealth, rented out rooms in his house to lodgers. One of his tenants, who headed a family of six and paid 30 dirhams a month for rent, wrote to al-Kindi and asked if two relatives could stay with him for a month. Al-Kindi called the man in and subjected him to a tongue lashing, demanding an extra 10 dirhams for the two additional lodgers, and at the same time lecturing him on the problems that landlords had to put up with from the devious ways of their tenants.

Al-Jahir (781–869) himself was an exceptionally interesting figure. He was from a very poor black family of East African origin who had moved to Basra, where as a boy he supported himself selling fish along one of the canals. He educated himself by listening to the scholars who lectured at the mosques and other gathering-places in Basra, before moving to Baghdad, where he became a highly popular writer and acquired a series of wealthy and powerful patrons. He is credited with more than two hundred works, including treatises on philosophy, zoology, psychology, history, theology, kalam, lexicography, rhetoric, and Arabic grammar, of which thirty survive. Aside from the *Book of Misers*, his best known work is *Kitab al-Hayawan* (*Book of Animals*), an encyclopedia in seven volumes, with descriptions and anecdotes of more than 350 types of animals, its original ideas including basic notions of natural selection through the survival of the fittest, the influence of the environment, and the notion of the interdependence of creatures through their food chain, of which he gives the following example:

> The mosquitoes go out to look for their food as they know instinctively that blood is the thing which makes them live. As soon as they see the elephant, hippopotamus or any other animal, they know that the skin has been fashioned to serve them as food; and falling on it, they pierce it with their proboscises, certain that their thrusts are piercing deep enough and are capable of reaching down to draw the blood. Flies in their turn, although they feed on many and various things, principally hunt the mosquito… All animals, in short, cannot exist without food, neither can the hunted animal in turn escape being hunted in his turn.

Medicine was another branch of science highly esteemed in Islam, as is evident in one of the *hadith*, or sayings, attributed to the Prophet Muhammed: ‘The best gift from Allah is good health. Everyone should reach that goal by preserving it for now and the future.’

An early and great writer on Islamic medicine is Abu Bakr Muhammed ibn Zakariya al-Razi (ca. 854–ca. 930), the Latin Rhazes, who was born in Rayy, in a suburb of present-day Tehran. As a youth he is said to have played the lute before he began his studies in medicine and philosophy. According to Ibn Khallikan’s biography of al-Razi: ‘In his youth he played on the lute and cultivated vocal music, but, on reaching the age of manhood, he renounced these occupations, saying that music proceeding from between mustachios and a beard had no charm for him.’

Al-Razi learned medicine in Rayy and became the director of the hospital there before the age of thirty-two. Later he headed the hospital in Baghdad, where students came from afar to study with him. He is credited with 232 works, including treatises on virtually every aspect of medicine as well as works in philosophy, logic, mathematics, astronomy, cosmology, alchemy, theology and grammar, of which most are lost.

The most important of al-Razi's surviving medical works is *al-Hawi*, known in its Latin translation as *Continens*, the longest extant Arabic work on medicine, filling some twenty-five volumes. It was translated into Latin under the patronage of King Charles I of Anjou by the Jewish physician Faraj ibn Salim ('Farragut'), who completed it in 1279, after having spent most of his life in the task. His translation was printed five times between 1488 and 1542.

Al-Razi's treatise on smallpox and measles, known in Latin as *De Peste*, was translated into English and other western languages and published in forty editions between the fifteenth century and the nineteenth. He was famous as a physician in both the East, where he was called 'the unsurpassed physician of Islam', and the West, where he was known as 'the Second Galen'.

Al-Razi's medical writings are characterised by his greater emphasis on observational diagnosis and therapy than on the theory of illnesses and their cures. Theories of illnesses and the scholarship surrounding them are constantly evolving, but in the most basic terms, they concern the ideas that people have to explain why they become ill or remain healthy. Whenever he writes about a particular malady he summarises all that he has read on the subject in Greek and Indian sources in Arabic translation as well as in the works of earlier Islamic physicians, adding his own opinion, an approach that he also took in his philosophical treatises. The titles of some of his works reveal his sense of humour concerning the limitations and misuse of the medical profession, such as his treatises *On the Fact that even Skillful Physicians Cannot Heal all Diseases*, *Why People Prefer Quacks and Charlatans to Skilled Physicians*, *On Why Some People Leave a Physician if he is Intelligent* and *Why Ignorant Physicians, Common Folk, and Women in the Cities are more Successful than Scientists in Treating Certain Diseases – and the Physician's Excuse for This.*

Al-Biruni's biography of al-Razi credits him with eighty works on philosophy, of which only a few short treatises and fragments survive. Al-Razi's extant philosophical writings show that he differed with Aristotle's rejection of the void as well as in the doctrine of natural motion, holding instead that all bodies tend to move toward the centre of the earth. Al-Razi followed Democritus in saying that matter consisted of atoms separated by a void, their relative separation determining their primary qualities such as density. He believed in the Pythagorean doctrine of metempsychosis, or the transmigration of souls. He followed Plato's *Timaeus* in holding that the five eternal principles are matter, space, time, the soul and the *demiurge*, or creator, known in Arabic as *bari*. Al-Razi's belief in the eternity of the soul and its eventual freedom from the body ran counter to the Islamic doctrines, as did his rejection of revelation and prophecy. The latter belief caused him to be branded a heretic and infidel by many of his successors.

Al-Razi's alchemical writings are also well known, particularly the *Book of Secrets*. Here he is less interested in the esoteric philosophical background of alchemy than in the chemical substances, processes and laboratory equipment involved. Among the substances that he studied was *naft*, or petroleum, which in modern times was to become the principal source of wealth of a number of Islamic countries in the Middle East. He also worked with oil lamps, or *nafata*, for which he used both vegetable oils and refined petroleum as fuel.

Al-Razi wrote on magic and astrology as well as on alchemy, and his work in these fields influenced the first natural philosophers in western Europe. One of his works, entitled *Of Exorcism, Fascinations, and Incantations*, discusses the use of those occult practices in causing and curing diseases. Those who followed al-Razi's lead searched for the Elixir of Life, the Philosopher's Stone, talismans and the magical properties of plants and minerals.

Unlike Plato and the Islamic philosophers who followed him, al-Razi did not believe that only the elite few are capable of understanding philosophy, which he said was accessible to all humans as a way of life and was their only means of salvation.

Al-Razi's most famous work is the *Kitab al-Tibb al-Ruhani*, known in its English translation as the *Book of Spiritual Physick*. This is a treatise on ethics based on Plato's concept of the Soul from the *Republic*, and was a companion volume to the *Kitab al-Mansuri*, known in its Latin translation as the *Liber Almansoris*, named for Abu Salih al-Mansur, prince of Kirman and Khorasan, which dealt with the 'Bodily Physick'.

The *Spiritual Physick* is divided into twenty chapters, whose headings reveal the character of the book: Of the Excellence and Praise of Reason; Of Suppressing the Passion, with a Summary of the Views of Plato the Philosopher; Summary Prolegomena to the Detailed Account of the Evil Dispositions of the Soul; Of How a Man may Discover his Own Vices; Of Repelling Carnal Love and Familiarity, with a Summary Account of Pleasure; Of Repelling Conceit; Of Repelling Envy; Of Repelling Excessive and Hurtful Anger; Of Casting Away Mendacity; Of Casting Away Miserliness; Of Repelling Excessive and Hurtful Anxiety and Worry; Of Dismissing Grief; Of Repelling Greed; Of Repelling Habitual Drunkenness; Of

Repelling Addiction to Sexual Intercourse; Of Repelling Excessive Fondness, Trifling, and Ritual; Of the Amount of Earning, Acquiring, and Expending; Of Repelling the Strife and Struggle in Quest of Worldly Rank and Station, and the Difference between the Counsel of Passion and Reason; Of the Virtuous Life; Of the Fear of Death. In the chapter on drunkenness, al-Razi addresses a poem to those addicted to drink:

When shall it be within thy power
To grasp the good things God doth shower
Though they be but a span from thee,
If all thy nights in revelry
Be passed, and in the morn thy rise
With fumes of drinking in thine eyes
And heavy with its wind, ere noon
Return to thy drunkard's boon?

Al-Razi describes his own moderate lifestyle in *The Philosophical Way of Life*, where he says that so far as indulgence and self-denial are concerned 'I have never gone beyond the upper and lower limits I have defined', noting that he had always devoted himself to scholarship. A contemporary describes al-Razi's routine in his last years, when he continued to practice as a physician despite his failing sight.

> He used to sit in his reception room with his students around him, surrounded by *their* students, and then still other students. A patient would enter and describe his symptoms to the first one he met. If they did not know what was wrong, he would progress to the next group. If they did not know, al-Razi himself would discuss the case. He was generous, dignified and honest with the people – so compassionate with the poor and sick that he would supply ample food for them and provide them with nursing care ... He was never seen to be taking notes or transcribing information, and I never went in to see him without finding him writing out a draft or a revision ... He went blind at the end of his life.

Al-Razi's failing sight was apparently caused by a cataract that developed in his later years. He refused surgery to have the cataract removed, saying that he had seen enough of the world. A poem that he wrote in his last days reveals the spirit in which he faced death:

Truly I know not – and decay
Hath laid his hand upon my heart,
And whispered to me that the day
Approaches, when I must depart –
I know not whither I shall roam,

Or where the spirit, having sped
From this its wasted fleshly home,
Will after dwell, when I am dead.

The next great Islamic philosopher-scientist after al-Kindi and al-Razi was Abu Nasr Muhammed al-Farabi (ca. 870–950). Al-Farabi, known in Latin as Alpharabius, was probably of Turkish origin, born at Farab in Transoxania, the region beyond the Oxus River (the modern Syr Darya) in Central Asia. He took courses in law and music at Bukhara then went to Merv, where he studied logic under a Syriac-speaking Nestorian scholar named Yuhanna ibn Haylan, whom he accompanied to Baghdad during the reign of Caliph al-Mu'tadid (r. 892–902). During the caliphate of al-Muktafi (r. 902–8) he moved to Harran with Ibn Haylan, where according to his own account, quoted by al-Khattabi, he completed his study of Aristotle's *Posterior Analytics*. 'After this,' according to al-Khattabi, 'he travelled to the land of the Greeks and stayed in their land for eight years until he completed [the study of the] science[s] and learned the entire philosophic syllabus.' His Greek studies would have been done at the university in Constantinople, where the study of ancient Greek philosophy had been revived during the patriarchate of Photius (r. 858–67, 877–86). This was part of a cultural revival in Byzantium that coincided with the flowering of Islamic knowledge and culture under the early 'Abassid caliphs.

Al-Farabi returned to Baghdad ca. 910 and remained there until 942, teaching and writing. He then moved to the court of the Hamdanid prince Sayf al-Dawlah in Damascus and Aleppo. He is credited with more than one hundred works, of which 33 have survived, including 12 in philosophy, 4 each in mathematics and music, 3 each in astronomy, physics and literature, 2 in medicine, and 1 each in chemistry and zoology.

He was deeply influenced by both Plato and Aristotle, and made an effort to reconcile Platonic and Aristotelian ideas when they conflicted. His goal was to revive the Aristotelianism taught at Alexandria in late antiquity, which had been transmitted to Islam by a succession of teachers, one of the last of whom may have been his own mentor Yuhanna ibn Haylan. Al-Farabi writes of this in his *Appearance of Philosophy*, where he says that the teaching of some of Aristotle's logical works was suppressed by the Christian bishops of Alexandria, and that thenceforth those works could only be taught privately until the coming of Islam.

Al-Farabi sought to give philosophy precedence over law, using Greek thought to reinterpret Islamic culture. His writings can be divided into three categories: introductory works on philosophy, commentaries on and paraphrases of Aristotle, and his own original theses.

The first category comprises mostly introductions to the ideas of Plato and Aristotle. The introductory works include the *Book of Indication of the Way to Happiness*; *Book on Attaining Happiness*; *Philosophy of Plato, its Parts and the Order of these Parts*; *Philosophy of Aristotle*; *Book of Common Views of Two Philosophers, Divine Plato and Aristotle*; *Directing Attention to the Way of Happiness*; *Terms Used in Logic*; and *Paraphrase of the 'Categories'*.

This first category of the works of al-Farabi also includes a general thesis called *The Ennumeration of the Sciences*, known in one of its Latin translation by Gerard of Cremona as *De Scientiis*. Al-Farabi's system for classifying the sciences was modified and elaborated upon by the Arabic scholars who succeeded him. The main branches of the sciences in his system are the Science of Language; the Science of Logic; the Mathematical Sciences; Physics and Metaphysics, Divine Science; and political philosophy, Jurisprudence, and Theology. The principal branches are further subdivided, so that the Mathematical Sciences are listed as Arithmetic, Geometry, Optics, Astronomy, Music, Science of Weights, and Mechanical Artifices. Al-Farabi, in his introduction, points out the advantages to be gained in studying his book: 'The book can be of use to the educated layman who wants to gain an overall impression of all the sciences, as well as for people who wish to be taken as scholars.'

Al-Farabi attacked astrology in his *Ennumeration of the Sciences*. Despite his opposition to astrology, al-Farabi still includes it with observational and mathematical astronomy as part of the 'Science of the Heavens'.

The second category of al-Farabi's writings includes commentaries on and paraphrases of Aristotle's *Nicomachean Ethics* and the whole of the *Organon*, his logical works, namely *Categoriae* (*Categories*), *De Interpretatione* (*On Interpretation*), *Analytica Priora* (*Prior Analytics*), *Analytica Posteriora* (*Posterior Analytics*), *Topica* (*Topics*) and *De Sophististicis Elenchis* (*On Sophistical Refutations*). His commentary on the *Nicomachean Ethics* puts forward his views on the necessity of guidance and education: 'Some men need little guidance, others a great deal of it. In addition, even when a man is guided ... he will not, in the absence of external stimulus and something to rouse him, necessarily do what he had been taught and guided to do. This is how most men are. Therefore they need someone to make all this known to them and rouse them to do it.'

The third category comprises al-Farabi's original philosophical works, the best known of which is *The Principles of the Opinions of the People of the Excellent Virtuous City*. Here, following the example of Plato's *Republic*, al-Farabi examines the metaphysical basis of the ideal Islamic state. Using Aristotle's world-picture as his model, he develops an hierarchical cosmology based on six principles, namely the First Cause, the Secondary

Causes, the Active Intellect, Soul, Form and Matter. The First Cause is associated with the outermost sphere of the heavens; the Secondary Causes are incorporeal Intellects embodied in the nested spherical shells of the stars, the sun, the moon and the five planets; while the Active Intellect controls the terrestrial world, composed of earth, water, air and fire, which in various combinations form humans, animals and inanimate objects.

Al-Farabi's writings include commentaries on Euclid's *Elements* and Ptolemy's *Almagest*, as well as an *Article on Vacuum*, a *Treatise on the Necessity of the Art of Chemistry*, a *Book of Spiritual Clever Tricks and Mysteries of Nature on the Subtlety of Geometric Figures*, a *Book of High Reasoning on Elements of the Science of Physics*, a treatise *On Objections to Galen with Regard to His Discrepancy with Aristotle about Organs of the Human Body* and a treatise *On Rhetoric and Poetry*.

Al-Farabi also wrote several treatises on musicology, the most important of which is *The Great Book of Music*. The theoretical part of the book, which is based mostly on Greek musicology, begins with a discussion of the physics of sound, where al-Farabi for the most part follows Aristotle. The rest of the book is devoted to musical practice concerning the various types of instruments used in the Islamic world, particularly the lute, which al-Farabi apparently played to perfection. He was also a composer, and some of his works were played in the rites of the Sufi brotherhoods, a number of them surviving today in the dervish orders of Turkey.

Ibn Khallikan tells an interesting story of al-Farabi's last days in Damascus at the court of Sayf al-Dawlah, who one evening asked him if he would like to hear some music. Al-Farabi said that he would, and a number of musicians in turn were brought in to play for him, but he found fault with each of them. Sayf al-Dawlah then said to him, 'Have you any proficiency in this art?', and al-Farabi answered 'Yes', whereupon he prepared to play before the prince and his companions. Ibn Khallikan then goes on to tell of al-Farabi's enchanting performance:

> He then drew from his waist a leather bag, opened and drew from it some reeds, which he put together. Then he played on them, whereupon all who were at the *majlis* [assembly] laughed. Then he took them to pieces and put them together another way, and when he played on them everyone in the *majlis* cried. Then he took them to pieces [yet] again, put them together differently, played on them and everyone in the *majlis*, even the doorkeeper, fell asleep. And al-Farabi went out.

CHAPTER 6

From Baghdad to Central Asia

The translation activities in the *Bayt al-Hikma* gave rise to a new Arabic science that spread from Baghdad eastward to Central Asia and eventually westward to Africa and Spain, as the equivalent of the Islamic renaissance spread to many of the lands conquered by the Prophet Muhammed's followers.

Astronomy held pride of place among the sciences in many Islamic regions (though for those with a philosophical bent, divine science was more revered), and Arabic astronomers often waxed eloquent in extolling the utility and godliness of their field. Muhammed ibn Jabir al-Battani (ca 850–929) begins his astronomical tables by citing verses of the Qu'ran in praise of astronomy.

> Verily, in the creation of the heavens and of the earth, and in the succession of the night and of the day, are marvels and signs for men of understanding heart (iii, 187); Blessed be He who has placed in the heaven the signs of the zodiac, who has placed in it the lamp of the sun and the light-giving moon (xxv, 62); It is He who appointed the sun for brightness and the moon for a light, and has ordained her stages, that you may learn the number of the years, and the reckoning of time (x, 5).

According to Aydın Sayılı, the first observatories in Islam were founded by Caliph al-Ma'mun, who in 828 built one at Shammasiya in Baghdad and another at the Dayr Murran monastery on Mount Qasiyun near Damascus. The two most prominent figures associated with the Shammasiya observatory were al-Khwarizmi and Yahya ibn Abi Mansur, who is referred to by the eleventh-century historian Sa'id al-Andalusi as 'the senior of the astronomers of his age'. Both al-Khwarizmi and Ibn Abi Mansur worked at the *Bayt al-Hikma*, which has led some scholars to infer that the Shammasiya observatory was associated with the House of Wisdom.

The eleventh-century astronomer and polymath al-Biruni says that Ibn Abi Mansur and al-Khwarizmi made daily solar and lunar observations at the Shammasiya observatory in the years 828–9, including a determination of the autumnal equinox. He notes that similar observations were also made at the same time at Qasiyun, and that the two sets of measurements of the autumnal equinox were compared, taking into account the eight degree difference in longitude between Damascus and Baghdad.

Ibn Abi Mansur died in 829 and al-Mam'un appointed Khalid ibn 'Abd al-Malik al-Marwarudhi to head the observatory at Damascus and to prepare a *zij*, or an astronomical handbook with tables. According to the astronomer Habash al- Hasib (d. ca. 865): 'Al Ma'mun ordered him [Khalid] to make ready instruments of the greatest possible perfection and to observe the heavenly bodies for a whole year at Dayr Murran. Khalid did this and thereby attained to the truth concerning the positions of the sun and the moon across the heavens.'

The instruments used at the Shammasiya and Qasiyun observatories included astrolabes, gnomons, mural quadrants, azimuthal quadrants and armillary spheres. The Egyptian astronomer Ibn Yunus says that after the death of Ibn Abi Mansur his armillary sphere was sold at the Paper Maker's Market in Baghdad. Other sources reveal that the astronomers at the Shammasiya and Qasiyun observatories studied the motions of the planets along with those of the sun and moon, as well as measuring the obliquity of the ecliptic, the rate of precession of the equinoxes, and the length of the tropical year, the time between two spring or autumn equinoxes. Another astronomical activity sponsored by al-Ma'mun was the measurement of the latitude and longitude of Baghdad and Mecca in order to determine the direction or *qibleh* of Mecca from Baghdad. This was done by simultaneous observations of lunar eclipses at Baghdad and Mecca, the distance between the two cities having been measured by al-Ma'mun's surveyors.

According to Habash al-Hasib, the early Islamic astronomers at Baghdad and Damascus based their work on what they had learned from the Greek astronomers, particularly Ptolemy, and their observations were made to correct whatever errors there might be in the ancient astronomical tables and bring them up to date.

The first of the new Islamic scientists in the generation after the founding of the *Bayt al-Hikma* was the astronomer Muhammed al-Battani. Al-Battani was from Harran, the birthplace of Thabit ibn Qurra, his older contemporary. He too was of Sabean origin, but unlike Thabit he became a Muslim, as indicated by his first name. His date of birth is unknown, but since his earliest recorded astronomical observation was made in 877 it has been suggested that he was born before 858. This information is from the *History of Learned Men* by Ibn al-Qifti (d. 1248), who says that al-Battani 'composed an important *zij* containing his own observations of the two luminaries [sun and moon] and an emendation of their motions as given in Ptolemy's *Almagest*'.

Ibn al-Qifti goes on to say that al-Battani continued to make observations until 918 and that he died in 929. The *zij* that he refers to are the *Sabean Tables* (*al-Zij al-Sabi*), known in its Latin translation by Plato of Tivoli in the first half of the twelfth century as the *Opus astronomicum*, where the author's name is given as Albategnius.

The instruments known to have been used by al-Battani are an astrolabe, a gnomon, an armillary sphere, a parallactic ruler, which he calls 'the long alidade', and a mural quadrant, which he equipped with an alidade, according to al-Biruni. Al-Battani mentions the latter instruments in connection with his measurements of the obliquity of the ecliptic: 'We have observed it in this time of ours with the parallactic ruler and the mural quadrant ... after having made their divisions very precise and securing them in their place as carefully as possible.'

Al-Battani's theoretical astronomy is derived almost entirely from Ptolemy and from his immediate Arabic predecessors. His most important contributions are his accurate observations, particularly concerning the variation of the apparent sizes of the sun and moon, the difference being most apparent in annular solar eclipses, when the moon's apparent diameter is a minimum.

The *Sabean Tables* were used by Copernicus, who refers to 'al-Battani the Harranite' in discussing the orbits of Mercury and Venus. Copernicus makes a number of other references to al-Battani, most notably his measurement of the sidereal year, which he compared to his own values as well as Ptolemy's and the one he attributed to Thabit ibn Qurra.

The sixteenth-century Danish astronomer Tycho Brahe also referred to al-Battani's observations, as did Kepler and Galileo. The definitive Latin translation of the *Sabean Tables* was published by the Italian orientalist C. A. Nallino, more than a thousand years after the Arabic original had been written.

Al-Battani's younger contemporary, the astronomer and mathematician Abu Ja'far al-Khazin, was also a Sabean, of Persian origin, perhaps from Khorasan province in eastern Iran, though this has never been proven. He spent part of his life at the court of the Buwahid emir Rukn al-Dawlah (r. 932–76) at Rayy, where in 960 he made his last known observation, a measurement of the obliquity of the ecliptic. He is presumed to have died at Rayy in the following decade.

Al-Khazin is credited with twelve works in astronomy and eleven in mathematics. All that survives of his astronomical writings are nine extant mathematical texts, one complete astronomical text and fragments of his tables, while his *Commentary of the Almagest* appears not to have survived. This latter seems to have been an important work, as evidenced by references to it by later Islamic scholars, most notably al-Biruni. One of his lost works, the *Book on the Secret of the Worlds*, first mentioned in the seventeenth century, could have been a new world model based on Ptolemy's *Planetary Hypotheses*, which would be used a century later by Ibn al-Haytham in his criticism of certain elements of the Ptolemaic system.

One of al-Khazin's mathematical works – which is preserved in Oxford – is a treatise on the impossibility of solving equations of the type $x^3 + y^3 = z^3$. This is a special case of what came to be known as Fermat's Last Theorem, written by the French mathematician Pierre de Fermat ca. 1637, i.e., 'It is impossible for a cube to be written as the sum of two cubes or a fourth power to be written as the sum of two fourth powers, or in general for any number which is a power greater than the second to be written as a sum of two like powers.' Fermat wrote this statement in the margin of a copy of the *Arithmetica* by Diophantus, followed by an additional comment noting that 'I have a truly marvelous demonstration of this proposition which this margin is too narrow to contain.' But Fermat never supplied the proof, which eluded many of the world's great mathematicians for more than three and one-half centuries. The problem was finally solved by Andrew Wiles, a British mathematician working at Princeton, who in May 1995 published his proof of Fermat's Last Theorem in the *Annals of Mathematics.* The books and articles written on this great discovery mention the succession of famous mathematicians who worked on this problem over the course of two millennia, from Diophantus to Fermat to Wiles, but there was not a single mention of al-Khazin, whose pioneering work on this subject has been irretrievably lost.

The Persian astronomer 'Abd al-Rahman al-Sufi (903–86) was known in the West as Azophi. Little is known of his life and career except his association with the Amir al-Umara, who captured Baghdad in 945 and for more than a century afterwards acted as protectors of the 'Abbasid caliphs, reducing them to the role of mere puppets. He worked in Shiraz as court astronomer of 'Adud al-Dawlah (r. 949–82), for whom he determined the obliquity of the ecliptic by observing the winter and summer solstices in the years 969–70.

Al-Sufi is credited with five works in astronomy and one in mathematics. He is best known for his *Treatise on the Constellations of the Fixed Stars*. This is a critical revision of Ptolemy's star catalogue, based on at least some of his own observations, which became a classic of Arabic astronomy for many centuries afterwards and later became known to the West through a Castilian translation.

The old Arabic star names that he used were adopted by most later Islamic astronomers and have made their way into modern stellar terminology. The illuminated manuscripts of the *Treatise* are among the most beautiful in Islamic science. The paintings show forty-eight constellations, with tables giving the position, magnitudes and colours of all of the stars. Each of the constellations is shown in two facing views, one as it would look to an observer on earth, the other as it would appear on the celestial sphere to a viewer outside. The mythological figures are shown in varying cultural costumes – mostly Central Asian, but some Buddhist and Chinese in the older manuscripts with later manuscripts showing them in dress that accords with the style of the period – so that in the constellation that bears his name Perseus is dressed in a flowing Arabic robe, as he brandishes his sword in one hand and with the other holds the severed head of Medusa by her long hair.

The most outstanding Islamic physician in the latter half of the tenth century was Ali ibn al-Abbas al-Majusi (c. 925–94), the Latin Haly Abbas. Majusi means 'Zoroastrian', although he himself was a Muslim, born near Shiraz (though some sources say it was Ahvaz). He received his medical training under the physician Abu Mahir ibn Sayyar, after which he directed the Baghdad hospital named for 'Adud al-Dawlah (d. 983), to whom he dedicated his only medical treatise, the *Kitab al-Maliki* (*The Royal Book*), known in its Latin translation as *Liber regius*. The main interest of this book today is al-Majusi's assessment of his Greek and Arabic predecessors, including al-Razi.

The *Kitab al-Maliki* consists of twenty chapters, evenly divided between the theory and practice of medicine. His surprisingly accurate description of pleurisy and its symptoms is evidence of the state of Islamic medicine at the time: 'Pleurisy is an inflamation of the pleura, with exudation which pours materials over the pleura from the head or chest … Following are the four symptoms that always accompany pleurisy: fever, coughing, pricking in the side, and difficult breathing.'

Al-Majusi stressed the importance of proper diet, bathing, rest and exercise for a healthy body and mind, and he wrote on the relationship between psychology and medicine. He emphasised the importance of psychotherapy in treating psychosomatic illnesses, one of which he recognised as unrequited love. His writings on poisons, including their symptoms and antidotes, represents the beginning of medieval toxicology. He wrote on the use of opiates and problems of drug addiction as part of his general discussion of medicines, and he also emphasised chemotherapy. He opposed contraception, as well as the use of drugs to induce abortion except when the physical or mental health of the mother was endangered. Here and in other medical issues he urged physicians and medical students to uphold the highest standards of medical ethics, as stated in the Hippocratic oath.

Abu'l Wafa al-Buzjani was born in 940 in Buzjan, now in Iran, and in 959 he moved to Baghdad, where he remained for the rest of his life, passing away there in 997 or 998. He made observations at the Baghdad observatory and wrote two astronomical treatises, the most important of which is his *Kitab al-Majisti*. Buzjani's choice of title reflects the importance of spherical trigonometry for mathematical astronomy, the subject of *The Almagest*. His main contribution in this work is his improvement in the trigonometric tables used in astronomy, achieved through his methods for approximating the sine function and solving problems in spherical trigonometry. He was also a major figure in the introduction of the sine theorem of spherical trigonometry.

Abu'l Wafa is credited with thirteen treatises on mathematics, including commentaries on Euclid, Diophantus, Hipparchus and al-Khwarizmi, though we know nothing of their actual content. Two of his original works are treatises on applied mathematics, entitled *A Book about What is Necessary for Scribes, Dealers, and Others from the Science of Arithmetic* and *A Book about what is Needed by Artisans for Geometric Constructions*. He also wrote two books on musical theory, one of them a revision of Euclid's work on music and the other a *Treatise on Rhythms*. Abu'l Wafa has been honoured by giving his name to a crater on the moon.

Abu'l Wafa's best known student was Abu Nasr Mansur ibn Iraq, who in turn was the teacher of the famous al-Biruni. Abu Nasr was born in the second half of the tenth century in Khwarazm, and belonged to the Banu 'Iraq family who ruled that region until it was conquered by the Ma'muni dynasty in 995. He spent most of his life in the service of two successive emirs of that dynasty, 'Ali ibn Ma'mun and Abu'l-'Abbas Ma'mun, who supported a number of other scientists, including al-Biruni and Ibn Sina. When Abu'l-'Abbas Ma'mun died, ca. 1016, Abu Nasr and al-Biruni were captured by the Ghaznavids and taken as prisoners to the court of Sultan Mahmud al-Ghaznawi in Ghazna (now Ghazni in Afghanistan). Abu Nasr spent the rest of his days in Ghazna, passing away there ca. 1036.

Abu Nasr is credited with 30 works, 11 of them in mathematics and 19 in astronomy. His most important discovery in mathematics, which he shares with Abu'l Wafa, is the sine law in trigonometry. The most important of Abu Nasr's extant writings is his *Improvement of the Spherics of Menelaus*. However, the most complete Arabic version of that work was produced by Tusi, who brought together several different translations.

Abu Rayhan al-Biruni was born in 973 at Kath on the Oxus, one of the two old capitals of Khwarazm, presently the town of Beruni named for him in Uzbekistan. Al-Biruni was very young when he began his studies with Abu Nasr, and he was only seventeen when he made his first recorded astronomical observation, a measurement of the meridian solar altitude at Kath, from which he computed its terrestrial latitude. Five years later he made an observation of the summer solstice near Kath, but then he was caught up in the civil war that erupted in Khwarazm, and had to flee the country for a time. He refers to this disturbance in his *Tahdid nihayat al-amakin*, or *The Determination of the Coordinates of Cities*: 'After I had barely settled down for a few years I was permitted by the Lord of Time to go back home, but I was compelled to participate in worldly affairs, which excited the envy of fools, but which made the wise pity me.'

Al-Biruni was back in Kath by 997, for on 24 May of that year he observed a lunar eclipse there. Abu'l Wafa observed the same eclipse from Baghdad, and by noting the difference in time of the two observations they were able to compute the difference in longitude between the two places.

Around the year 1000 al-Biruni went to Gurgan at the south-east corner of the Caspian Sea, where the Ziyarid ruler Qabus had re-established himself. Al-Biruni dedicated to Qabus his earliest extant major work, the *Chronology*. There he refers to seven other works that he had already written, none of which have survived. The titles of these lost treatises indicate that al-Biruni had already begun researches in fields in which he would do much of his later studies, for five of these works were in astronomy and astrology, two on history and one on mathematics.

During the year 1003 al-Biruni observed two lunar eclipses in Gurgan, one on 19 February and the other on 14 August. Then the following year he observed a lunar eclipse in Jurjaniyye, at that time ruled by the emir Abu'l-'Abbas Ma'mun brother-in-law of the powerful Turkish sultan Mahmud al-Ghaznawi of Ghazna, in what is now Afghanistan. As he notes in his *Tahdid*, al-Biruni was deeply involved in Khwarazmian political affairs, particularly in the delicate negotiations between Abu'l-'Abbas Ma'mun and Sultan Mahmud. Mahmud conquered Khwarazm in 1017 and executed Abu'l-'Abbas Ma'mun, after which al-Biruni was exiled to the village of Lamghan north of Kabul, where he recorded a solar eclipse on 14 October 1018. Later he entered the service of Sultan Mahmud as court astronomer and astrologer, accompanying him on campaigns that conquered most of the small Persian kingdoms in the region and expanded the Ghaznavid domains well into the Indian subcontinent.

The knowledge that al-Biruni obtained in these campaigns enabled him to write his major work, in its abbreviated version titled the *Tahqiq ma li'l Hind min Maqalatin*, or *A Verification of What is Said on India*, known in its English translation as *Alberuni's India*. He also met and questioned emissaries sent to Sultan Mahmud's court from the Volga Turks, Uighur Turks and the Chinese, from whom he obtained geographical and other information on Central Asia and the Far East.

Sultan Mahmud died in 1030 and was succeeded by his son Mas'ud. Two years later Mas'ud was assassinated in a coup that brought to the throne his son Mawdud, who reigned until his death in 1050. Al-Biruni enjoyed the patronage of all three sultans, outliving Mawdud by a few months.

Based on his own bibliography, al-Biruni is credited with 146 works, of which 22 are extant. His works include 39 on astronomy, 23 on astrology, 16 on literature, 15 on mathematics, 10 on geodesy and mapping theory, 9 on geography, 5 on chronology, 4 on history, 3 on religion and philosophy, 2 on time measurement, 2 on mechanics, 2 on medicine and pharmacology, 2 on mineralogy and gems, 2 on magic, 2 on India, 1 on meteorology, and 9 on a variety of other subjects, including detailed descriptions of his observational instruments and inventions.

Al-Biruni's native tongue was Khwarizmian, an Iranian language with no scientific vocabulary, and, through the languages of the courts, religion, literature and science, he learned both Arabic and Persian. He also acquired sufficient knowledge of Greek, Syriac and Hebrew to use dictionaries in those languages. His knowledge of Sanskrit was such that, with the aid of scholars from India, he was able to translate Indian scientific works into Arabic. His Arabic was so fluent that he was able to compose poetry in that language and to quote from the classics in his treatises.

A survey of al-Biruni's extant works reveals the enormous range of his interests and the originality of some of his researches, his accomplishments placing him in the uppermost rank among all scientists.

His work on the *Chronology of Ancient Nations* is divided into twenty-one chapters, of which the first deals with the various definitions of the solar day and the second with the several ways of defining the year – solar (i.e. by the cycle of seasons), lunar, lunar-solar, Julian, Persian – as well as the notion of intercalation, i.e., adding extra days to the lunar calendar to make it compatible with the solar year. The last section of the book is on stereographic projection and other methods of mapping a sphere on to a plane, as done in the astrolabe.

Al-Biruni's short thesis *On the Astrolabe* is considered to be the most useful work of its kind. His even briefer thesis on the sextant describes the giant mural sextant built at Rayy by the astronomer al-Khujandi for the emir Fakhr al-Dawlah, which al-Biruni may have inspected. The *Tahdid nihayat al-amakin* describes al-Biruni's measurements of the geographical coordinates of cities through astronomical and terrestrial observations. He applied his method to determine the difference in longitude between Baghdad and Ghazna, his final result being in error by only eighteen minutes of arc.

Al-Biruni's *Book on the Multitude of Knowledge of Precious Stones* is a study of the physical properties of various solids and liquids, including precious and semi-precious stones, whose specific gravities he measured using an ingenious balance based on Archimedes' principle. He also writes of the medical properties of these materials and their philological and philosophical significance.

The first three of the thirty chapters in the treatise *On Shadows* include a philosophical discussion of gnomonics, the study of shadows cast by gnomons, as well as studies of the nature of light, shade and reflection, along with references to shadows in Arabic poems. The remaining chapters describe the use of the gnomon in determining the seasons of the year, the time of day, Muslim prayer times, the cardinal directions, the *qibleh* and the determination of heights of objects as well as terrestrial and celestial distances. The mathematical background of the gnomon is analysed as well as its use in sun-dials of various types.

The *Canon of Al-Mas'udi* is the most comprehensive of al-Biruni's extant astronomical works, with more observational information and mathematical derivations than in the typical *zij*, along with detailed numerical tables designed to solve all of the problems encountered by a professional astronomer or astrologer. It is organised into eleven sections, the first two of which deal with general cosmological principles, most notably that the earth is the stationary centre of the hierarchical universe. Sections 3 and 4 deal with plane and spherical trigonometry, including tables of the trigonometric functions that are more precise than in other works available at that time; section 5 repeats much of the material in the *Tahdid*, covering geodesy and mathematical geography, with a table of geographic coordinates of cities and other places; sections 6 and 7 are on the sun and moon, respectively, using essentially Ptolemaic models but with many of the observations by al-Biruni himself; section 8 computes lunar and solar eclipses and the times of first visibility of the lunar crescent; section 9 includes a table with the coordinates of 1,029 stars, slightly more than in Ptolemy's *Almagest*; section 10 is on the planets, with tables of their celestial coordinates, visibility and 'stations', i.e., where they begin and end their retrograde motion; and section 11 deals with the astronomical background of astrology.

The *Kitab al-tafhim*, known in its English translation as *Elements of Astrology*, became a well-known Islamic text of instruction in astrology, with Arabic and Persian versions both possibly translated in al-Biruni's lifetime. Nevertheless, al-Biruni emphasised that he did not really believe in astrology, for he thought that the 'decrees of the stars' had no place in the exact sciences. In the final chapter al-Biruni discusses the movements of the planets in great detail, using the epicycle theory to explain their retrograde motion.

Another of al-Biruni's extant astrological works is his treatise *On Transits.* The term 'transit' is used when one planet passes one another in the celestial sphere, an event that was believed to have astrological significance in Indian and Persian cosmologies, as evidenced by references to lost works in al-Biruni's treatise.

Al-Biruni's treatise *On Pharmacology* consists of 720 articles on drugs, most of which are identified by their names in Arabic, Greek, Syriac, Persian and an Indian language, and sometimes also in Hebrew or in less common languages or dialects such as Khwarizmian. Each drug is described along with its places of origin and its therapeutic properties, with the sources of information fully documented by al-Biruni, who disclaims his own medical competence on the subject.

Al-Biruni's *Kitab al Jamahir fi ma_rifat al-Jawahir* (*Book of the Multitudes, On the knowledge of Gems*) is divided into two parts, with the first devoted to precious and semiprecious stones, the second to metals, where he uses other Arabic sources along with his own translations. The various materials are described, along with their principal sources. The weights of the metals are given relative to gold, and the prices of pearls and emeralds are tabulated in terms of their size. The book also contains observations on technological processes such as the casting of iron, the production of steel, and the mining and purification of gold.

Arguably Al-Biruni's most famous work today is his monumental treatise on India, running to 656 pages in its English translation, whose subtitle describes it as *An account of the religion, philosophy, geography, chronology, customs, laws and astrology of India.* Al-Biruni says at the end of his book that the background information he has provided 'will be sufficient for any one [in Islam] who wants to converse with the Hindus, and to discuss with them questions of religion, science, or literature, on the very basis of their own civilisation'.

Chapter 26 is 'On the shape of Heaven and Earth according to the Hindu astronomers'. The most interesting part of this chapter is its last section, where al-Biruni discusses the possibility, raised by the Indian astronomer Brahmagupta, that the Earth rotates on its axis while the heavens remain at rest, as opposed to an older view that the Earth is stationary and the celestial sphere rotates about it. Al-Biruni refers to a book, now lost, that he himself wrote on the possible rotation of the earth, which he appears to have rejected.

Some of al-Biruni's most interesting ideas are preserved in his question and answer correspondence with Ibn Sina, which took place around the year 1000. Here al-Biruni criticised many of Aristotle's theories, such as the impossibility of a vacuum, while Ibn Sina defended them. Al-Biruni's speculations about celestial motion are particularly interesting, for he disagrees with Aristotle's doctrine of natural place and natural motion, proposing instead that the heavenly bodies do have gravity (i.e., weight) despite the fact that they move in circular orbits rather than toward the centre. He even seems to suggest that the heavens could have an elliptical motion without contradicting the laws of physics.

Al-Biruni's other accomplishments include a calculation of the earth's circumference, a geared calendar showing the motion of the sun and moon among the signs of the zodiac, a device for making accurate measurements of the specific gravities of liquids, a mechanical triangulation instrument for measuring distances such as the width of a river or the height of a minaret, and a mathematical method for determining the direction of Mecca from any point. But al-Biruni's works were never translated into Latin, and though he was extremely influential in the Islamic world and though there was some knowledge of him in al-Andalus he had little influence on the subsequent development of science in Europe.

Al-Biruni, who personally spread Muslim knowledge of the world as far as Central Asia and India, writes in his *Tahdid* of the universal character of Islam and its role in uniting many peoples in its embrace. 'And now Islam has appeared in the Eastern and Western parts of the world and has spread between Andalus in the West and parts of China and Central India in the East, and between Abyssinia and Nubia in the South and the Turks and Slavs in the North. It has, as never before, united the different nations in one bond of love ...'

CHAPTER 7

The Cure of Ignorance

Islamic natural philosophy and medicine reached their peaks with the work of Abu ‘Ali al-Husain Ibn Sina (ca. 980–1037), known to the West as Avicenna, the ‘Prince of Physicians’.

According to his autobiography, which he dictated to his disciple Abu-‘Ubayd al-Juzjani, Ibn Sina was born and educated near Bukhara, in present-day Uzbekistan. He writes that ‘when I reached the age of ten I had mastered the Qur’an and a good deal of literature to such an extent that I evoked great amazement’, after which he notes that his father ‘sent me for a while to a greengrocer who used Indian arithmetic and I would thus learn from him’.

His father then hired Abu ‘Abdallah al-Natili, ‘who claimed to be a philosopher’, and under his tutelage Ibn Sina studied Aristotle’s *Organon*, Euclid’s *Elements* and Ptolemy’s *Almagest.* He says that he soon outstripped his tutor, who ‘took leave of me’, and ‘I occupied myself on my own with Determining the Validity of books, both original texts on Physics and Metaphysics, and the gates of the Philosophical Sciences began opening before me.’ Then, as he writes, he embarked on a study of medicine.

> Next I desired [to learn] medicine and I read the books that have been written on this subject. Medicine is not one of the difficult sciences, and therefore I excelled in it in a very short time, to the point where distinguished physicians began to read medicine with me. I cared for the sick, and there opened up to me indescribable possibilities of therapy which can only be acquired through experience. At the same time I was also occupied with jurisprudence and would engage in legal disputations, being now sixteen years of age.

He goes on to say that during 'The next year and a half I devoted myself entirely to reading Philosophy... So I continued until all the Philosophical Sciences became deeply rooted in me and I understood them as much as is humanly possible ... Having mastered Logic, Physics and Mathematics, I had now reached Theology.' Then he read Plotinus' *Enneads* 'but did not understand what it contained ...', despite rereading it forty times. He was at his wit's end until he read a copy of al-Farabi's *On the Purposes of the Metaphysics*, and immediately everything in Aristotle's book became clear to him. 'I rejoiced at this and the next day I gave much in alms to the poor in gratitude to God Exalted.'

By the time he was seventeen Ibn Sina was such a renowned physician that he was summoned to Bukhara by Sultan Nuh ibn Mansur (r. 976–97), who was suffering from an illness that his own doctors could not cure. Ibn Sina says he collaborated with the court physicians and cured the sultan, who in gratitude gave him free use of the royal library. He says that the library contained books by the ancients that he had never even heard of before, which he soon devoured. 'So that by the time I reached my eighteenth year I had completed my study in all the Philosophical Sciences. At that time my retention of Knowledge was better, but today my grasp of it is more mature; otherwise the Knowledge is the same, nothing new having come to me since.'

Ibn Sina's first work, written at the age of seventeen, was a short treatise entitled *Compendium on the Soul*, dedicated to Sultan Nuh ibn Mansur. Ibn Sina describes this work in his last treatise, *On the Rational Soul*, written forty years later: 'As a matter of fact, I happened to write at the beginning of my career forty years ago a summary treatise setting forth the knowledge about the soul and related matters by following the method of those who engage in philosophy through research; whoever wishes to find out about the soul should study this thesis because it is appropriate for students who do research.'

The eighth chapter of the *Compendium* deals with 'The Stages of the Human Soul from Inception to Perfection'. Ibn Sina writes that the species of rational beings possesses a faculty called the rational soul, 'by means of which it is able to conceptualise the intelligibles'. He says that 'This faculty... does not in itself possess any intelligible forms, but these rather come about within it in one of two ways'. One of these ways is 'divine inspiration ... as in the case with ... our belief that the whole is greater than the part'. The other way is to acquire these forms 'through syllogisms and Discover [them] through demonstration'. As examples of the second way he presents Logic, Physics, Mathematics and Metaphysics, which includes Universal Science and Theology. He goes on to say that some inspired and sanctified people can acquire knowledge without recourse to the second way. 'None shall gain the enjoyment of this rank except prophets and messengers of God, peace and prayers be upon them.'

Three years later Ibn Sina completed three works commissioned by two learned neighbours in Bukhara. The first of these, *The Compilation*, or *Philosophy for 'Arudi*, was written for Abu 'l-Hasan 'Arudji, a neighbour of his in Bukhara. This was an attempt to write a comprehensive work on 'all the sciences except mathematics', i.e., the whole of the Aristotelian canon. The other two were *The Available and the Valid*, a multivolume work on philosophy, and a two-volume treatise on ethics called *Piety and Sin*. Ibn Sina says in his autobiography that these works were written for another neighbour of his named Abu Bakr al-Baraqi, who 'asked me to comment on the books on Philosophy and so I composed *The Available and the Valid* for him in about twenty volumes, and I also composed a book for him on Ethics which I called *Piety and Sin*. These two books exist only in his possession because he never lent them to anybody to copy from.'

Ibn Sina's life changed after the death of his father, when he became involved in a career in the service of a succession of princes that kept him on the move for the rest of his days, as he notes in his autobiography.

> Then my father died. Independent now, I took over one of the administrative posts of the Sultan. However, necessity led me to abandon Bukhara and move to Gurganj, where Abu-l-Husayn al-Suhayli, a lover of the Philosophical Sciences, was a minister. I was introduced to the Prince there, 'Ali ibn Ma'mun; at the time I was in lawyer's garb,... They fixed me for a monthly salary which provided enough for someone like me. Then necessity forced me to move to Nasa, and from there to Baward, and then to Tus, then to Samanqan, then to Jajarm, and then to Jurjan. I was planning to go to Prince Qabus, but it happened meanwhile that he was taken and imprisoned in a fortress where he died. Then I departed for Dihistan, where I fell very ill. I returned to Jurjan, and there I became associated with Abu 'Ubayd al-Juzjani.

Ibn Sina was thirty-two when he met al-Juzjani, who became his devoted disciple, and to whom he dictated his autobiography up to the time of their meeting. Al-Juzjani then took up the story from that time on, noting that 'From this point I mention these episodes of the Master's life of which I myself was a witness during my association with him, up to the time of his death.'

According to al-Juzjani, shortly after Ibn Sina arrived in Jurjan, ca. 1013, he wrote a treatise called *The Provenance and Destination* for his patron Abu Muhammad as-Shirazi, an 'amateur of these sciences'. The treatise was divided into three parts, the first two of which deal with the first principle and the being that emanates from it, while the third treats the survival of the human soul.

At this time Ibn Sina began writing his major medical text, *al-Qanun fi'l-tibb*, the *Canon of Medicine*, an encyclopedic work that took him more than a decade to complete. While in Jurjan he also wrote a book on logic called *The Middle Summary* and a treatise on astronomy entitled *Summary of the Almagest*, in which he said that 'he introduced ten new figures into the observations' and claimed that 'he had things that had never been discovered before'.

The following year Ibn Sina and al-Juzjani moved on to Rayy, 'one of the glories of the land of Islam', the birthplace of Harun al-Rashid. Ibn Sina joined the court of the Buyid emir Majd al-Dawlah, whom he successfully treated for melancholia. While he was in Rayy Ibn Sina composed a treatise called *The State of the Human Soul*, in which he developed more fully the ideas he had presented in the third part of *The Provenance and Destination*. In the introduction he says that book 'contains the marrow [of the theory] about the state of the human soul arrived at through demonstrative proofs'.

Ibn Sina, accompanied by al-Juzjani, moved from Rayy to Qazwin and then to Hamadan, where he entered the service of the emir Shams al-Dawlah brother of Majd al-Dawlah, whom he successfully treated for colic. Ibn Sina says that when he left his grateful patient's presence he was 'loaded with many costly robes ... having passed forty days and nights at the palace and become one of the Emir's intimates'.

Ibn Sina accompanied Shams al-Dawlah as his personal physician in a war against the Kurds, and on his return he was raised to the rank of vizier. But the army for some reason would not accept this, 'fearing for themselves on this account', and Ibn Sina says that 'they surrounded his house, hauled him off to prison, pillaged his belongings ... They even demanded that he should be put to death; but this the Emir refused, though he was agreeable to banishing him from the State, being anxious to conciliate them.' Ibn Sina was forced to hide in a friend's house for forty days, but then Shams al-Dawlah suffered another attack of colic and brought him back to the palace, reinstating him as vizier.

Al-Juzjani writes that at this time he suggested that his master write a commentary on the philosophy of Aristotle. Ibn Sina replied that he had little spare time to do so, because during the day he was in attendance on Shams al-Dawlah and in the evening was working on his *Qanun*, but 'if you agree that I should compose a book setting forth these parts of the sciences that I believe to be sound, not disputing therein with any opponents nor troubling to reply to their arguments, I will do so.'

Ibn Sina thus began writing the *Kitab al-Shifa*, the longest of his extant works, a compendium of Aristotelian philosophy known in English as the *Book of Healing*, also called *The Cure* and sometimes *The Cure of Ignorance*. According to Dimitri Gutas, Ibn Sina's choice of the title was influenced by the sixth-century scholar Paul the Persian, who described 'Aristotle's oeuvre as a "course of treatment" (*Shifa*) that cures "the diseases of ignorance"'. Ibn Sina's prologue to the *Shifa'* states that his compendium of Aristotelian thought 'will help remove the veils of fanciful notions' from philosophy.

Ibn Sina spent his evenings with his disciples listening to them read from his works, convivial gatherings that recalled the symposia of Plato's Athens. As al-Juzjani writes: 'I would read the *Shifa'* and another in turn the *Qanun*. When we had each finished our allotted portion, musicians of all sorts would be called in and cups brought out for drinking, and in this manner we spent the rest of the time. Studying was done by night because during the day attendance upon the Emir left him no spare time.'

Shams al-Dawlah died in 1021 and was succeeded by his son Saman al-Dawlah, who reappointed Ibn Sina as vizier. Ibn Sina was unsure of the stability of his new patron's regime, and to hedge his bet he went into hiding in the house of a friend and entered into secret correspondence with a rival ruler, 'Ala' al-Dawlah, emir of Isfahan. His secret correspondence was discovered by Saman al-Dawlah's vizier Taj al-Mulk, who found Ibn Sina's hiding place and had him imprisoned in a castle at Fardjan, fifty-five miles from Hamadan. As Ibn Sina wrote at the time of his imprisonment: 'That I go in you see, so that's without doubt./ What's uncertain is whether I ever come out.'

Al-Juzjani, in his account of these events in the year 1022, tells of how Ibn Sina, at his request, made an effort to complete the *Shifa'* while he was in hiding, 'without having any book at hand or source to consult, accomplishing the work entirely from memory'.

> Each day he wrote fifty leaves, until he had completed the natural sciences and metaphysics save for the books of zoology and botany. He commenced work on the logic, and wrote one part of this; but then Taj al-Mulk suspected him of corresponding with 'Ala' al-Dawlah, and disapproving of this instituted a search for him. The master's whereabouts were betrayed by an enemy, and he was committed to a fortress called Fardjan, where he remained for four months.

During the four months that Ibn Sina remained in Fardjan he completed three works, one of which was a medical treatise called *Colic*, a subject on which he had become expert through his treatment of Shams al-Dawlah. The second of the three works was *al-Hidaya*, or *The Guidance*, which had a full section on the Metaphysics of the Rational Soul.

The third was *Risalat Hayy ibn Yaqzan*, an allegory of the human intellect, also known as *Treatise of the Living the Son of the Wakeful*. This was the first of a cycle of what are termed Ibn Sina's 'Visionary Recitals', three in number, the others being *The Bird* and *Salman* and *Absal*. *Hayy ibn Yaqzan* inspired the Andalusian Muslim philosopher Ibn Tufayl to write a book with the same theme and title. Ibn Sina's allegory was translated into Hebrew by the Spanish Jewish poet, philosopher and scholar, Abraham ben Ezra, who used it to write a poetic work called *Hay ben Meqitz*. Aaron W. Hughes writes of the allegories of Ibn Sina, Ibn Tufayl and Abraham ben Ezra in *The Texture of the Divine*: 'All three are highly literate accounts that offer elaborate descriptions of the structure of the universe and the changing role of the individual within it. All three texts poetically describe the protagonist's intellectual and mystical ascent, and all culminate in the protagonist's imaginative apprehension of the divine.'

'Ala' al-Dawlah captured Hamadan in 1023, forcing Saman al-Dawlah and Taj al-Mulk to flee to Fardjan, joining Ibn Sina. When 'Ala' al-Dawlah withdrew Sama' al-Dawlah and his vizier returned to Hamadan, along with Ibn Sina, who went to live there with an old friend to whom he dedicated a treatise on *Cardiac Therapies* that he wrote soon after his return.

While Ibn Sina was at Hamadan he completed the *Qanun*, his major work on medicine, which comes to about a million words, divided into five books. Book I, 'Generalities', is devoted to a discussion of medical theories such as that of the four humours (blood, bile, black bile and phlegm), the causes and symptoms of disease, hygiene, modes of therapy, treatment by regimes and diet, the use of drugs, and the procedures involved in cupping, blood-letting, cautery, evacuation and general surgery. Book II, 'Materia Medica', is a survey of the properties and uses of some 760 drugs, as well as the application to medicine of his scientific method, in which he favoured empirical methods over abstraction and formalism. Book III, 'Head to Toe Diseases', discusses diseases of organs or systems, twenty-one in all, including the brain, nerves, eyes, ears, joints and even the nails of the fingers and toes. Book IV, 'Diseases That are not Specific to Organs', begins with a treatise on fevers, their types and symptoms; it then goes on to teach minor surgery and the treatment of wounds, sprains, dislocations, poisons, bites by insects, snakes and animals, and skin diseases. Book V, 'Compound Drugs', is a manual of pharmacology as an integral part of medical practice.

Ibn Sina codified Greek medical knowledge translated into Arabic in his *Qanun*, basing, for example, his description of anatomy and physiology principally on Galen and his *Materia Medica* on Dioscorides. His *Qanun* remained the most popular medical textbook for six centuries, not only in the Muslim world but also in Christian Europe. It was first translated into Latin as the *Canon Medicinae* between 1150 and 1187 by Gerard of Cremona, and in the last three decades of the fifteenth century it was published in fifteen printed editions along with one in Hebrew. Another twenty editions of the *Canon* were printed in the sixteenth century and several more in the seventeenth century along with one in Arabic issued in Rome in 1593.

Da Monte, in his commentary on the *Canon* published in 1554, said that Avicenna, as he was known in Latin, had written his text 'because he saw that neither the Greeks nor the Arabs had any book that could teach the art of medicine as an integrated and connected subject'. It was still used as a textbook in the medical school at Montpellier as late as 1650. Although Ibn Sina's adoption of the ancient theory of the four humours makes the theoretical basis of the *Canon* seem preposterous today, as does his cures for ailments such as werewolfism. But as an encyclopedia of medicine as a teaching discipline, divided into practical and theoretical medicine the *Canon* remained unsurpassed up until the beginning of the twentieth century, at least according to the opinion of Professor John Urquhart. Writing in the *British Medical Journal* in 2006, Urquhart said: 'If the year were 1900 and you were marooned and in need of a guide for practical medicine, which book would you want by your side? My choice was Ibn Sina.'

Meanwhile Ibn Sina resumed his secret correspondence with 'Ala' al-Dawlah, who promised to give him refuge. Al-Juzjani describes how he and Ibn Sina fled from Hamadan disguised as dervishes and made their way to the emir's court in Isfahan, where he received a royal welcome. 'At court he was received with the respect and consideration he so richly merited. 'Ala' al-Dawlah appointed every Friday night a meeting for learned discussion before him, to be attended by all the scholars according to their various degrees, the Master Abu Ali among them; in these gatherings he proved himself quite supreme and unrivalled in every branch of learning.'

'Ala' al-Dawlah made Ibn Sina a vizier, a rank that he held for the rest of his days, often accompanying the emir on campaign. The Muslim scholar Bayhaqi (d. 1174) writes of Ibn Sina's attractive appearance and manner when he paid court to 'Ala' al-Dawlah: 'He used to sit very close to the Emir, whose face became radiant with delight as he marveled at his good looks, and accomplishment and wit. And when he spoke all those present listened attentively, none uttering a word.'

On one of these campaigns, when ‘Ala’ al-Dawlah defeated the Kurds in 1027, Ibn Sina completed the *Shifa’*, which he had been working on for more than seven years. According to al-Juzjani, he also worked on the *Kitab al-Najah* while on that campaign: ‘So he finished the *Shifa’*, all but the botany and zoology, which he composed in the year when ‘Ala’ al-Dawlah marched to Sabur-Khwast; these parts he wrote *en route*, as well as the *Kitab al-Najah*.’

The organisation of the *Shifa’* follows the Aristotelian tradition for the classification of the sciences, which Ibn Sina had presented in the *Compendium on the Soul*, the *Compilation*, and undoubtedly also in *The Available and the Valid*. Ibn Sina’s prologue outlines the contents of his work, noting that it dealt with Aristotle’s logic and physics, Euclid’s geometry, Ptolemy’s astronomy, and the *Introduction to Arithmetic* by Nicomachus, after which he says ‘I then concluded the discipline of the mathematicians with an abridgment of the science of Music ... Finally, I concluded the book with the science that belongs to Metaphysics in accord with its parts and aspects, while referring in it [only] to the essential elements of Ethics and Politics.’

The first sections of the *Shifa’* to appear in Latin were the commentaries on Aristotle’s logic, on *De anima*, and on the *Physica*, which in the second half of the twelfth century were translated as the *Sufficientia Physicorum* by Domenicus Gundissalinus, the archdeacon of Segovia, working in collaboration with a converted Spanish Jew named Abraham ben Daud.

Around 1200 the English scholar Albert of Sareschal translated part of the Mineralogy section of the *Shifa’* into Latin under the title *De Mineralibu*s. Ibn Sina’s ideas about the formation of stones, mountains and fossils given there in the geological sections are remarkably accurate. He writes of how mountains became ‘petrified in the course of ages, the limits of which history has not preserved’. He goes on to say that it is because mountains are formed from earth that was formerly beneath the sea ‘that in many places, when they are broken, are found parts of aquatic animals such as shells, etc’.

Ibn Sina’s observations on the formation of stones, mountains and fossils were picked up by Albertus Magnus in the thirteenth century in his commentary on *De Mineralibus*, from which they were passed on to Leonardo da Vinci and other European scholars in the sixteenth and seventeenth centuries.

After completing the *Shifa’* he began writing a treatise called *an-Najat*, or *The Salvation*, which he completed that same year, using mostly material from works he had previously written. He says that he composed this in response to a request from friends, who had asked him to write a book that contained the absolute minimum of philosophical and scientific knowledge that an educated person should have 'to attain salvation from drowning in a sea of errors'.

He also composed a work in Persian called *Daneshname-ye 'Ala'i* for 'Ala' al-Dawlah, who had asked him for a digest of logic, physics, metaphysics, astronomy and music, of which he wrote only the first three. Here he acknowledges his debt to Aristotle, 'the leader of the wise and the guide and teacher of philosophers'.

Al-Juzjani added sections on astronomy and music as well as on arithmetic and geometry, thus completing the mathematical quadrivium.

Ibn Sina's last work of philosophical summation is his *Pointers and Reminders*, written sometime between 1030 and 1034. It consists of two parts, the first on Logic, the second on Physics and Metaphysics, each divided into ten chapters. He describes the book in the prologue to the first part: 'O you who are anxious to Ascertain the Truth: I have exposed to you in these Pointers and Reminders, Fundamental Principles and essential elements of philosophy; if sagacity takes hold of your hand it will become easy for you to Derive Corollary Principles from the former and work out the details of the latter.'

The two collections of writings known as *Appendices: Notes and Discussions* were probably completed in 1037, the year that Ibn Sina died. The *Notes* is a collection of writings in logic, physics and metaphysics, while the *Discussions* comprises philosophical questions and Ibn Sina's answers. Ibn Sina refers to the *Appendices* in the prologue to the *Shifa'*, which he wrote long after the work itself was completed: 'Then I thought it appropriate that I should write another book to follow this one. I have called it *Appendices*, and it will end with my life, finding its termination in whatever will have been completed every year. It is like a commentary to this book, Providing Corollaries to its Fundamental Principles and elaborating upon its briefly expressed concepts.'

When 'Ala' al-Dawlah went off to make war on the Ghaznavids in 1037 Ibn Sina accompanied him throughout the campaign, though he suffered a severe attack of colic, which he tried to treat himself. Al-Juzjani tells of how Ibn Sina, despite his illness, continued to serve the emir to the end, passing away in June 1037 after a march from Isfahan to Hamadan.

> He once more attended the court of 'Ala' al-Dawlah; however, he was incautious and indulged his sexual appetite too far, so that he was never wholly cured, suffering repeated relapses ... He therefore gave up treating himself, and took to saying, 'The manager who used to manage me is incapable of managing me any more; so it is no use trying

> to cure my sickness. So he continued some days, and was then transported to the Presence of his Lord. He was buried at Hamadhan, being 58 years old.

Ibn Sina's medical writings were translated into Latin and used as basic texts in Europe's medical schools until the seventeenth century. His *Canon of Medicine* was far ahead of its times in dealing with such matters as cancer treatment, the influence of the environment, the beneficial effects of physical exercise, and the need for psychotherapy, where he recognised the connection between emotional and physical states, including the heartache of unrequited love.

Ibn Sina wrote on light and the theory of vision in a number of his works, including the *Shifa'*, *Najat*, *Qanun* and *Danishnama*. He defended the Aristotelian intromission theory of vision, in which the visual rays proceed from the luminous object to the eye.

Ibn Sina was the first Muslim scientist to revive the impetus theory of John Philoponus, an attempt to explain why a projectile continues to move after it is fired. He described this impetus as 'a quality by which the body pushes that which prevents it moving itself in any direction'. He also calls it an 'impressed force', and describes it as a 'borrowed power' given to the projectile by the source of motion, 'just as heat is given to water by a fire'. The fourteenth-century French physicist Jean Buridan used the term '*impetus impressus*', defined as weight times velocity, revived by Galileo under the names '*impeto*' and '*momento*', which is proportional to the modern 'momentum', or mass times velocity. Newton's second law of motion, the basis of the new dynamics that he introduced in his *Principia*, published in 1687, says that the force acting on a body is proportional to the time rate of change of momentum.

One of Ibn Sina's most influential followers was Sayyid Zayn al-Din al-Juzjani (d. ca. 1070), who came from the Central Asian region of Khwarazm. His principal work is the *Treasury Dedicated to the King of Khwarazm*, a medical encyclopedia based on Ibn Sina's *Canon*, written in Persian, which contributed to the establishment of the scientific terminology for medicine, including pharmacology. Al-Juzjani's other writings include his *Medical Memoranda* and *The Aims of Medicine*, which, along with his *Treasury*, were the principal sources for the perpetuation of the medical teachings of Ibn Sina and his predecessors.

Al-Juzjani is remembered principally because of his association with Ibn Sina, whose tomb can still be seen in Hamadan. Ibn Sina had immense influence on the subsequent development of philosophy and medicine, both in the Islamic world and in Latin Europe. His ideas, which combined Platonic and Aristotelian concepts, had a profound effect on western thought in the thirteenth century.

Ibn Sina's accomplishments led A. C. Crombie to say 'I think we can agree with Roger Bacon's judgment that in its natural branches, Avicenna was "the man who completed philosophy as far as it was possible for him to do so".' Ibn Sina was also a gifted poet, as is evident from the verses of his *Poem on the Soul* quoted by A. J. Arberry, who ranks them 'among the sublimest composed in any language'.

Out of her lofty home she hath come down
Upon thee, this white dove in all the pride
Of her reluctant beauty; veiled is she
From every eye eager to know her, though
In loveliness unshrouded radiant....
And if the tangled net impeded her,
The narrow cage denied her wings to soar
Freely in heaven's high ranges, after all
She was a lightning-flash that brightly glowed
Momentarily o'er the tents, and then was hid
As though its gleam was never glimpsed below.

CHAPTER 8

Fatimid Cairo: The Science of Light

The Arabs conquered Egypt in the years 639–42 and established their first capital on the Nile just south of the delta, building a new town called Fustat. Egypt was administered as a province of the caliphate, first for the caliphs in Medina, followed by the Ummayads in Damascus, and then the ‘Abbasids in Baghdad.

Egypt was conquered in 969 by the Fatimids, a dynasty that claimed descent from Muhammad’s daughter Fatimah and ‘Ali, the fourth caliph. That same year the Fatimid caliph, al-Mu’izz (r. 969–75), built a new city near Fustat called al-Qahirah (the Victorious), which in the West came to be known as Cairo. Under the first two successors of al-Mu’izz – the caliphs al-Aziz (r. 975–96) and al-Hakim (r. 996–1021) – the Fatimid caliphate in Egypt became one of the most powerful states in the Islamic world, extending its sway over North Africa, Syria, the Hijaz and Sicily, while Cairo emerged as a cultural centre rivalling Baghdad in its brilliance.

During the years 969–72 al-Mu’izz built the great mosque of al-Azhar, ‘the Radiant’, which today houses one of the oldest Islamic centres of learning in the world. Al-Hakim founded the *Dar al-Ilm*, or House of Knowledge, a great and famous library. The fifteenth-century Egyptian historian al-Maqrizi writes that the *Dar al-Ilm* had forty rooms, its collection was rumoured to have included 18,000 manuscripts dealing with the ‘Science of the Ancients’.

One of the first astronomers Arabic scholars to live in Egypt was the geographer and historian Abu ‘l-Hasan al-Masudi. Al-Masudi was born near Baghdad late in the ninth century. He left Baghdad ca. 915 and travelled through Persia, Central Asia, India and the Near East, before finally coming to Egypt, where he spent his last years, dying in Fustat in 956 or 957.

Al-Masudi is credited with thirty-seven extant works, including writings on geography, history, law, theology, genealogy and government. Only two of his works have survived in their entirety. These are *Meadows of Gold and Mines of Gems*, a compendium of geography, geology and natural history completed in 947 and revised in 956, and *The Book of Indication and Revision*, a summary of his world-view and philosophy completed a year before his death. His magnum opus, the *Kitab Akhbar*, a world history in thirty-three volumes, is lost except for its first volume.

Al-Masudi took a critical approach to ancient sources, for he believed that knowledge accumulated and advanced in time. As he writes in *The Book of Indication and Revision*: 'And often a latter-day writer, since he discovers new things not known to previous generations, the sciences steadily progress to unknown limits and ends.'

The first astronomer to emerge in Fatimid Cairo was the astronomer 'Abd al-Rahman Ibn Yunus (d. 1009). Ibn Yunus was born in Fustat, and began his astronomical observations in 977, two years after al-Aziz became caliph. When al-Hakim succeeded to the caliphate in 996, at the age of eleven, his keen interest in astrology led him to sponsor Ibn Yunus, who continued his observations until 1003. Ibn Yunus spent the next four years completing the *al-Zij al-Hakimi al-kabir*, the *Hakimid Tables*, dedicated to Caliph al-Hakim.

The *Hakimid Tables* is much longer than the *zij* of al-Battani and contains twice as many tables. The unique feature of this work is that it begins with a list of the observations made by Ibn Yunus and his predecessors, dating back as far as those of the Banu Musa in Baghdad. The list includes records of forty planetary conjunctions and thirty eclipses, the latter being used by the nineteenth-century astronomer Simon Newcomb in determining the secular acceleration of the moon.

The first chapter of the *Hakimid Tables* also deals with the Muslim, Coptic, Syrian and Persian calendars, with detailed instructions for converting dates from one calendar to another, as well as tables for determining the dates of Easter and Lent in the Coptic and Syrian calendars.

Material from the *Hakimid Tables* was used in the *zijs* of later Arabic astronomers, most notably those of al-Tusi and al-Maghribi, done in the thirteenth century at the famous observatory at Maragha in Persia. Ibn Yunus also wrote the collection of astronomical tables known as the *Kitab ghayat al-intifa* (*Very Useful Tables*), astronomical tables for time-keeping used in Cairo until the nineteenth century, principally for determining the times of the five occasions of daily prayer.

Ibn Yunus was also a renowned astrologer. The astrological predictions in his treatise, *On the Attainment of Desire*, are based on the heliacal risings of Sirius when the moon is in each of the twelve signs of the zodiac, as well as on the day of the week in which the Coptic year begins.

A biography of Ibn Yunus by his contemporary al-Musabbihi has been preserved in the works of later writers. This biography reveals that Ibn Yunus was an eccentric who paid no attention to his personal appearance and was considered a figure of fun in Cairo. One day, while apparently in good health, he told his friends that he would die seven days later, whereupon he locked himself in his house and put his manuscripts in order. He then recited the Qu'ran continuously until he died, passing away on the very day that he had predicted, after which his son sold his manuscripts by the pound in the Cairo soap market.

The most renowned of all the scientists who worked in Fatimid Cairo is Abu 'Ali al-Hasan al-Haytham (ca. 965–ca. 1041), known in the West as Alhazen. The most extensive sources for Ibn al-Haytham's life are two biographies written some two centuries after his death, one by Jamal al-Din ibn al-Qifti (d. 1248) and the other by Ibn Abi Usaybi'a (d. 1270).

Both biographers agree that Ibn al-Haytham was born in Basra, in Iraq. According to Ibn Abi Usaybi'a, he first held the post of minister at Basra, but later dedicated his life to the study of philosophy.

Ibn al-Qifti says that Ibn al-Haytham went from Iraq to Egypt during the reign of Caliph al-Hakim, to whom he had proposed a construction that would regulate the flow of the Nile. When Ibn al-Haytham inspected the Nile he was deeply impressed by the many ancient structures along the river, and he realised that if a water-control project was at all possible the ancient Egyptians would have put it into effect long ago. He admitted this when he met with al-Hakim, who nevertheless offered him a position in some government department. Ibn al-Haytham accepted the post for fear of offending the caliph, a bloodthirsty tyrant who had executed many of his advisors and commanders. But he sought to avoid dealing with al-Hakim by pretending to be insane, whereupon he was confined to his house and remained there until the caliph's death in 1021. Ibn al-Haytham then put aside his pretence of madness and took up residence near the al-Azhar mosque, where, according to both Ibn al-Qifti and Ibn Abi Usaybi'a, he supported himself by teaching and by copying Euclid's *Elements* and Ptolemy's *Almagest*, and in his spare time working on his researches.

Ibn Abi Usaybi'a writes that in Ibn al-Haytham's later years he decided to ignore the rest of humanity and devote himself to seeking the truth as the surest way of gaining favour with God, a decision he attributed to his 'good fortune, or a divine inspiration, or a kind of madness'. His first studies were in theology, but he was so frustrated by this that he became convinced that truth was to be found only in 'doctrines whose matter was sensible and whose form was rational'. He concluded that such doctrines were to be found in the writings of Aristotle and in works on mathematics, physics and metaphysics.

Ibn Abi Usaybi'a gives lists of Ibn al-Haytham's works up to 2 October 1038, about three years before his death, consisting of ninety-two titles, fifty-five of which are extant, including works on mathematical, optical and astronomical subjects. One of the titles refers to a question that Ibn al-Haytham was asked in Baghdad in the year AH 418 (1027–8 AD). This would mean that he was in Baghdad for a time six years after the death of al-Hakim. But the list may not be complete, since Ibn al-Qifti states that he owned a book on geometry in Ibn al-Haytham's own hand dated AH 432, or 1040–1 AD, probably completed not long before he died.

Ibn al-Haytham wrote works on logic, ethics, politics, poetry, music and theology, as well as summaries of the writings of Aristotle and Galen, but none of these have survived. His extant works are in astronomy, mathematics and optics, the fields where he is generally agreed to have made his most significant and enduring contributions, particularly on light and vision.

Ibn al-Haytham's masterpiece is his *Kitab al-Manazir*, known in English as the *Optics*, divided into seven books. Although he doesn't say so explicitly, it is clear that he takes as his starting point Ptolemy's *Optics*. He says at the beginning of the preface to the first book of his *Optics* that earlier investigators had reached the limits of their studies, but their 'views on the nature of vision are divergent and their doctrines on the nature of sensation not concordant. Thus perplexity prevails, certainty is hard to come by, and there is no assurance of attaining the object of inquiry.' He then goes on to say that his work will study this obscure subject using both the natural and mathematical sciences.

He says that he set out to clarify the subject by 'recommencing the inquiry into its principles and premises, starting the investigation by an induction of the things that exist and a review of the conditions of the objects of vision'. He goes on to say that once this was done he would 'ascend in the inquiry and reasonings, gradually and in order, criticising premises and exercising caution in the drawing of conclusions'.

Book I of the *Optics*, entitled 'On the Matter of Vision in General', presents Ibn al-Haytham's general theory of light and vision, supported by his observations, experiments and geometrical demonstrations. The book is divided into a Preface and seven other chapters, of which chapter 3 is on his experiments and observations, while chapter 5 is on the structure of the eye and the others on Ibn al-Haytham's theory of vision. His description of the structure of the human eye is based on the writings of Galen, but with adaptations to fit in with his own theory of vision.

His intromission theory of vision involves 'visual rays' projected in straight lines from each point on the surface of a luminous body to a corresponding point on the pupils of the eyes, which act as lenses, from where the optic nerve transmitted the 'distinct form' of the object to the brain so as to form an image.

He says that light is an essential form in self-luminous bodies, while it is an accidental form in those that become luminous from an outside source. Bodies such as air or water are transparent in their essential form and transmit light, while an opaque body such as a stone by its nature absorbs light and thus become a self-luminous source. The light radiated by a self-luminous body is called 'primary', while light is 'secondary' if it is emitted by a body irradiated by external sources. Both primary and secondary light diminish in intensity with distance from their source. Every point in a luminous source of light, whether it be primary or secondary, emits radiation 'in the form of a sphere' in all directions rectilinearly.

Ibn al-Haytham uses observations, experiments and geometrical constructions to support his statements and theories. For example, he supports his statement that light travels in a straight line by using a room that embodied the principle of a camera obscura, or pin-hole camera, a principle that was possibly known also to Aristotle. He was the first to give an explanation of this device, a dark chamber into which light is admitted through a small hole, and he used it to demonstrate the rectilinear propagation of light in several situations, such as the radiation from the stars and planets.

Book II describes Ibn al-Haytham's theory of the psychology of perception. As he writes in the preface: 'We shall now show in this Book the different conditions of the radial lines and distinguish their characteristics; we shall also give a detailed account of all properties perceptible to sight, and show the manner in which sight perceives each of them, and distinguish the ways in which sight perceives visible objects and show how they differ from one another.'

Book III is entitled 'On Errors of Direct Vision and Their Causes.' The second chapter, On what needs to be advanced for clarifying the discussion on errors of sight, deals with binocular vision, beginning with a description of how our eyes are coordinated when we examine an object.

> When the beholder fixes his sight on an object, the axes of both eyes converge on the object, meeting at a point on its surface. When he

> contemplates the object, the two axes will move together over the surface of the object and together pass over all of its parts ... When both eyes are observed as they perceive visible objects, ... their respective actions and movements will be found to be always identical.

Books IV and V deal with catoptrics, i.e., phenomena involving reflection. His statement of the law of reflection, already established by Ptolemy, was based on experiments with both plane and curved mirrors, the latter including concave and convex surfaces of spherical, conical and cylindrical shape.

Book VI discusses errors in perception resulting from vision by reflected rays, including errors in the size, location and number of images.

The seventh and final book of the *Optics* is devoted to dioptrics, i.e., phenomena involving refraction. Ibn al-Haytham gives a detailed description of his improved version of Ptolemy's instrument for measuring refraction, which he used to study the bending of light at plane and spherical surfaces with air-water, air-glass, and water-glass interfaces. He summarises the results of his experiments in a set of eight rules for the relation between the angles made by the incident and refracted rays with the normal, or perpendicular to the surface. The last two rules state that a denser refractive medium bends the light more toward the normal, while a rarer medium bends it away. Ibn al-Haytham was aware, as Ptolemy had been, that these two rules stem from the fact that the velocity of light is greater in the rarer medium than in the denser one. Ibn al-Haytham's theory introduced a new method, that of resolving the velocity of light into two independent components, one along the normal and the other perpendicular to it, where the first component changed in the refraction while the second remained constant. This approach, called the 'parallelogram method', was used by a number of European physicists from the thirteenth century onwards, both in the study of light and of motion. It was later used by Witelo and Kepler, and Descartes applied it in his successful deduction of the sine law of refraction in 1637.

Ibn al-Haytham's *Optics* is considered to be one of the most important and influential works ever produced in Islamic science. The *Optics* was first translated into Latin in the late twelfth or early thirteenth century, under the titles *De aspectibus* or *Perspectiva.* The *Perspectiva* influenced Roger Bacon, John Pecham and Witelo, all of whom were writing on optics in the third quarter of the thirteenth century. Through them Ibn al-Haytham's theories influenced Johannes Kepler, whose optical writings represent the beginning of the modern science of optics. According to David C. Lindberg, writing in 1976, 'In the final analysis, Kepler's position on the character of visual perception, is not very different from Alhazen's.'

Ibn al-Haytham refers to the work of an older contemporary named Abu Sa'd al 'Ala Ibn Sahl, who is the author of a recently-discovered treatise on optics. This treatise dated 983–85, entitled *A Proof of the Fact That the [Celestial] Sphere is not Perfectly Transparent*. It is evident from this treatise, and from the reference to him by Ibn al-Haytham, that Ibn Sahl correctly stated the law of refraction, which was not discovered in Europe until the seventeenth century. Although Ibn al-Haytham was aware of Ibn Sahl's discovery, he did not use it in his own study of refraction.

Besides the *Optics*, the extant optical writings of Ibn al-Haytham include twelve other works: *Treatise On the Light of the Moon*, *Treatise On the Rainbow and the Halo*, *Treatise On the Appearance of the Stars*, *Treatise On Spherical Burning Mirrors*, *Treatise On Paraboloidal Burning Mirrors*, *Treatise On the Quality of Shadows*, *Treatise On the Light of the Stars*, *Treatise On the Mark on the Face of the Moon*, *Discourse on Light*, *Treatise On the Burning Sphere*, *The Solar Rays* and *Treatise On the Form of the Eclipse*.

In his *Treatise On the Light of the Moon* Ibn al-Haytham writes that he accepted the arguments of 'learned investigators' that the moon gets its light from the sun, but he remarks that 'the ancients' never explained how the moon emitted this light. He shows that the lunar surface does not act as a mirror in reflecting sunlight to the earth, but emits the radiation as if it were a self-luminous source. He demonstrates this with an instrument called a dioptra (in English, diopter) or sighting tube, using a slit of adjustable length through which different parts of the moon could be viewed through an aperture in a screen at the other end of the tube.

The *Treatise On the Rainbow and the Halo* is an attempt to explain the rainbow in terms of the reflection of sunlight from the 'thick and moist air' after a shower. He attempts, mistakenly, to reduce the rainbow to a special case of reflection from a concave mirror. Nevertheless his approach was the starting point for the more successful attempt to explain rainbows by the Persian polymath Kamal al-Din al-Farisi (1267–1319).

In the *Treatise On Spherical Burning Mirrors* Ibn al-Haytham shows that spherical mirrors do not have a unique focal point, but that the focal point of each ray of a parallel beam of light depends on how far it is from the optical axis, i.e., the axis of symmetry. He also studied refraction by a glass sphere, and showed that the focal points of the light rays passing through it also depend on their distance from the optical axis. Thus he is the discoverer of spherical aberration, anticipating the work of Kepler and other researchers on optics in the seventeenth century.

In his *Treatise On Parabaloidal Burning Mirrors* Ibn al-Haytham refers to the writings of 'Archimedes and Anthemius of Tralles and others' in recognising that paraboloidal mirrors have a unique focal point. But he says that they did not demonstrate this, whereas he did. He then goes on to give detailed explanations of how to construct spherical and paraboloidal mirrors from steel.

Ibn al-Haytham's *Treatise On the Quality of Shadows* is a study of gnomonics, how the shadows cast by gnomons are used in astronomy and time-keeping. In his study he defines darkness as the total absence of light, and shadow as the partial absence of light. He distinguishes between umbra (*zulma*), and penumbra (*zill mahd*), the two shadow cones of the earth, in the first of which no sunlight penetrates, while in the second there is some solar radiation.

Ibn al-Haytham's *Treatise On the Light of the Stars* attempts to refute the theory of 'certain philosophers' that the stars, i.e., the fixed stars and the five visible planets, shine by reflected sunlight. His argument was based on the fact that the stars and the planets do not show phases like the moon, which shines through reflected sunlight. This is of course erroneous, for although the fixed stars are self-luminous, the planets, like the moon, shine through the light they reflect from the sun. He concluded that since the moon was not self-luminous it must be composed of a different substance than the other celestial bodies.

In his *Treatise On the Mark on the Face of the Moon* Ibn al-Haytham attempts to explain the dark patches on the lunar disk. After considering various possibilities, one being that the patches were shadows cast by mountains on the moon, which Galileo would observe with his telescope in 1609, he concludes that the marks were due to variations of what he called the 'opacity' of the lunar surface, which is equivalent to the modern term 'albedo', the relative reflecting power of a surface.

Ibn al-Haytham's *Discourse on Light* is a concise explanation of the observations and ideas that he presented more fully in the *Optics*, beginning with the statement that a complete investigation of light must combine the natural and mathematical sciences.

His *Treatise On the Form of the Eclipse* gives the theory of light passing through circular apertures. In particular, he examines the question of why the partially eclipsed sun casts a crescent-shaped image, while the crescent or partially eclipsed moon gives a circular image through the same opening. Here he makes use of the principle that he had established in the *Optics*, that every point in a luminous object is the source of light that is emitted rectilinearly from that point. The thesis is of particular interest because it describes the camera obscura, the device that eventually led to the development of photography. His treatise shows that he thoroughly understood how the *camera obscura* functioned.

The extant writings of Ibn al-Haytham also include twenty works on astronomy. One of the most popular of these was a treatise *On the Configuration of the World*, which was translated into Castilian, Hebrew and Latin. His aim in this work was to give a physical model of the Ptolemaic astronomical system rather than a mathematical theory, one that would be 'more truly descriptive of the existing state of affairs and more obvious to the understanding'. The model that he chose was that of the homocentric spheres of Eudoxus, which he described fully and clearly without going into unnecessary technical detail, which may be why this work was so popular.

Another of his extant astronomical writings, known in its Latin translation as *Dubitationes in Ptolemaeum* and in Arabic as *Al-shukuk-ala Batlamyus* is a critique of three of Ptolemy's works: the *Almagest*, the *Planetary Hypotheses* and the *Optics*. So far as the *Almagest* was concerned, Ibn al-Haytham's main objection was to the equant, which merely disguised the fact that the planets in Ptolemy's model did not move with uniform velocity around the earth as a centre.

Ibn al-Haytham's *Commentary on the Almagest* is the longest of his extant astronomical works. His intellectual autobiography gives a longer version of the title of this thesis, together with a statement of his purpose: 'Commentary and Summary of the *Almagest* with Proofs, in which only a few computations have been worked out, and if God prolongs my life and I find leisure in my time I shall resume a more comprehensive commentary that will take me into the numerical and computational matters.'

A particularly interesting part of the *Commentary* concerns Ibn al-Haytham's remarks on a passage in the *Almagest*. This is where Ptolemy says that celestial bodies appear enlarged when they are observed near the horizon, 'just as objects placed in water appear bigger than they are, and the lower they sink the bigger they are', because of 'exaltations of moisture surrounding the earth'. He interprets this effect as being due to the refraction of light by the atmosphere, using the same analogy as Ptolemy, and says that light from a star near the horizon will be 'deeper' in the atmosphere, 'and therefore it will be seen as larger because an object appears larger the deeper it is in water'. He then proceeds to give a geometrical derivation of this statement, using only the law of reflection.

His *Treatise On the Appearance of the Stars* deals with the optical problem discussed above. This treatise seems to have been written later than the *Commentary*, since it shows a deeper understanding of the part played by refraction.

Ibn al-Haytham's fame as a mathematician stems largely in the West from his solution to the so-called 'Alhazen's Problem' in Book V of his *Optics*. That is, from two points outside a circle and in its plane, to draw lines meeting at the circumference and making equal angles with the surface normal, or perpendicular, at that point. This leads to a fourth-degree equation, which Ibn al-Haytham solved by finding the intersection points of a circle and a hyperbola.

Aside from the mathematical analysis in the *Optics*, a score of Ibn al-Haytham's writings exclusively on mathematics have survived, most of them brief and varying considerably in importance. One of the longest and most important of these works is entitled *Solution of the Difficulties in Euclid's Elements*. Here he tried to prove Euclid's fifth postulate, defining parallel lines, one of several such attempts by Islamic mathematicians. Another of his longer mathematical works, *On Analysis and Synthesis*, was written to explain the methods necessary for finding and proving theorems and constructions, by illustrating their applications in arithmetic, geometry, astronomy and music, placing particular emphasis on the role of 'scientific intuition'.

Ibn al-Haytham influenced some of the most important physicists of the European renaissance, most notably Galileo, Descartes and Kepler, all of whom read translations of his *Optics*. Thus the early, pre-Newtonian science of light bears the imprint of Ibn al-Haytham, whose observations, experiments and theories represent a definite advance on what the ancient Greeks had accomplished, and were used by the men who created the new scientific doctrines that would emerge in western Europe in the seventeenth century.

CHAPTER 9

Ayyubid and Mamluk Cairo: Healing Body and Soul

The Fatimid dynasty came to an end in 1171 with the death of the last caliph, al-'Adid, who was succeeded by Salah al-Din ibn Ayyub (r. 1171–93), a Kurdish military commander known in the West as Saladin, who had taken control of Egypt two years before. Saladin thus established the Ayyubid dynasty, refortifying Cairo and building an imposing citadel that still stands, along with the defence walls that enclosed the inner city in his time. Using Egypt as his power base, Saladin went on to conquer Syria and Mesopotamia, defeating the Crusaders at the Battle of Hattin in 1187 and reconquering Jerusalem for Islam.

The leading intellectual figure in Cairo at the beginning of the Ayyubid period was the Jewish philosopher Rabbi Moses ben Maimon, better known in the West as Maimonides. Maimonides was born sometime between 1136 and 1138 at Cordoba in al-Andalus, the son of an accomplished rabbinic scholar and judge, as had been five generations of his forefathers. Around 1159 or 1160 the family moved to Fez in the Maghrib. There he received most of his secular education, studying philosophy, astronomy, mathematics and medicine, presumably with Muslim scholars, while he continued the study of rabbinical literature that he had begun at Cordoba.

Then in 1165 Maimonides left Fez with his family, and after a tour of the Holy Places in Palestine he settled in Egypt, first in Alexandria and then in Fustat, Old Cairo. There he began practising as a physician and became a rabbinic judge and unofficial head of the Jewish community. After the establishment of the Ayyubid dynasty in 1171 Maimonides became personal physician to Saladin's vizier, Fadil al-Baisami, and later to Saladin's son and successor, al-Aziz (r. 1193–98). At the same time he also tended the sick in Cairo, both Muslims and Jews. Besides his judicial and medical duties, Maimonides spent all of his spare time studying and writing, as he had since his earliest youth. But at times the press of his medical work left him no time for his studies, as he writes in a letter to his student Joseph ibn Aknin:

> I have acquired a high reputation among the great, such as the chief kadi [judge], the emirs, the house of al-Fadil and other city notables, who do not pay much. The ordinary people find it too far to come and see me in Fustat, so I have to spend my days visiting the sick in Cairo and when I get home I am too tired to pursue my studies in the medical books.

After Maimonides became personal physician to Sultan al 'Aziz his schedule became even more exhausting, as he wrote in a letter to Samuel ibn Tibbon:

> My duties to the sultan are heavy. I must visit him early every morning. If he feels ill, or if any of his children or harem are sick, I do not leave Cairo but spend the greater part of the day in the palace. If some of the court officials are ill I am there the whole day… even if there is nothing, I do not get back to Fustat until afternoon. Then I am tired and hungry and find the courtyard of my house full of people high and low, gentiles, theologians and judges, waiting for my return. I dismount, wash my hands and beg them to wait while I eat, my only meal of the twenty-four hours. Then I attend to the patients. They are queuing up until nightfall, sometimes till 2 a.m. I talk to them lying on my back because I am weak. When night falls I am sometimes too weary to speak. So no Israelites can have a private talk with me except on the Sabbath. Then they all come to me after the services, and I advise them what to do during the coming week … This is my routine.

Maimonides suffered from poor health in his later years, and in a letter to a group of scholars in what is today southern France in 1199 or later he writes that he had been 'ill for about a year' and even after his recovery he had to spend 'most of the day in bed'. In a later letter to the same group he writes that 'I can no more go out and come in. I have become old and gray headed, not by reason of years, but by the nature of my body which is well acquainted with disease.' He finally passed away in Fustat in 1204, when he would have been somewhere between sixty-six and sixty-eight years of age. He was buried at Tiberias in Palestine, where his tomb can still be seen, with this inscription: 'From Moses [the prophet] to Moses [Maimonides] there has arisen no one like him.'

The writings of Maimonides fall into four general categories: rabbinic works, philosophic works, medical works and miscellaneous writings. All but one of his scholarly works were written in Judeo-Arabic, the exception being the *Mishneh Torah*, his code of Jewish law, which is in Hebrew. The earliest of his rabbinic writings is his *Talmudic Commentaries*, which he completed before the age of twenty-three, while he was still in Fez. Only fragments of these commentaries have survived, and knowledge of them is based principally on the testimony of Maimonides himself. He says that he composed 'interpretative comments on three Orders [of the Babylonian Talmud], namely, [the Orders dealing with] holy days, women, and torts ...' He goes on to say that he also wrote about the ritual slaughter of animals and their use for food 'because of the great need of it'.

The earliest of the extant rabbinic writings of Maimonides is his *Commentary on the Mishneh*, which he began at the age of twenty-three and completed seven years later, by which time he had settled in Egypt. He says that his aim in writing a commentary on the Mishneh, the first post-Biblical Jewish code of laws, was to interpret it 'as the [Babylonian] Talmud does, to restrict myself to interpretations that are normative, and to omit any interpretation rejected in the Talmud'. Besides its material on Talmudic law, the *Commentary* also contains considerable material on scientific subjects such as astronomy, cosmology, psychology, zoology, botany and natural history. At the end of his commentary Maimonides asks the reader to pardon his errors, since it was written 'in exile and wandering from one end of the earth to the other, parts of it during journeys on land, others while going in ships on the sea'.

Maimonides' next major rabbinic work was his *Book on the Commandments*, which he completed in 1170. This is an attempt to codify the 613 commandments that were presented to Moses, according to the Babylonian Talmud. His introduction presents rules for determining which of these commandments should be included in Jewish law and which should be excluded. Maimonides' major work of rabbinic scholarship is the *Mishneh Torah*, his magisterial code of Jewish law in fourteen volumes written in Hebrew, which was completed in 1178, after he had 'laboured day and night for about ten continuous years in assembling this composition'. He writes in the introduction that in the *Mishneh Torah* he composed a work in which he 'assembles the entire Oral Torah, together with the positive ordnances, customs and negative ordinances...', so that everything would be clear 'to the small and to the great', and 'No one will ever require a further composition for any Jewish law.'

The *Mishneh Torah* is divided into fourteen books, beginning with *The Book of Knowledge*, which contains 'all the commandments that make up the foundations of the religion of Moses and that a person must know at the outset'. He concludes *The Book of Knowledge* by urging his readers to acquire wisdom if they would love God to the fullest, 'to the extent, of course, that a human being is able to understand and know'.

Maimonides links the proof for the existence of God with a simplified version of the Aristotelian First Mover of the celestial spheres. Maimonides writes that 'the celestial sphere rotates continually, and it is impossible to move without a mover, from which it follows that God moves the sphere with an infinite power'.

His cosmology is based on the world-view that Islamic philosophers had acquired from Aristotle, with its dichotomy between the terrestrial and celestial regions. According to this view, the terrestrial region was composed of the four elements earth, water, air and fire, while the celestial bodies were made of aether, the quintessential substance, and were set in nested transparent spheres that rotated around the immobile earth.

One section of the *Mishneh Torah* opens with a summary of Aristotle's theory of ethics, after which Maimonides goes on to describe a regime of diet and hygiene for achieving good health. He concludes this section by writing that 'I guarantee that all who obey the rules which I have laid down will stay free of disease ... until they die at an advanced age without ever needing a physician, while their bodies will be healthy and remain so through their lives.'

Other sections in the *Mishneh Torah* deal with natural philosophy to at least some extent, particularly those that have to do with the Jewish lunar calendar, such as *The Book of Times and Seasons*.

Maimonides' earliest philosophic work is *The Treatise on Logic*, which may have been composed while he was still in Fez. The attribution of this work to Maimonides has been questioned, but the consensus now seems to be that he is indeed the author, though he himself never mentions the treatise in his later works.

Maimonides' major philosophic work is *The Guide for the Perplexed*, an explanation of the fundamental theology and philosophy of Judaism, which he wrote in the years 1185–90. The *Guide* was addressed to his disciple Joseph ibn Aknin, to whom the book was dedicated. The title comes from his statement of purpose in the introduction.

> In my larger work, the *Mishneh Torah*, I have contented myself with briefly stating the principles of our religion and its fundamental truths, together with such hints as approach a clear exposition. In this work, however, I address those who have studied philosophy and have acquired sound knowledge, and who while firm in religious matters are perplexed and bewildered on account of the ambiguous and figurative expressions employed in the holy writings.

Maimonides notes that his purpose is to show that rational philosophy does not contradict Jewish beliefs, but rather that it helps a man to attain the ultimate state of happiness, which is the perfection of his intellect so that he can contemplate the divine.

Maimonides bases his cosmology on the five elements (four terrestrial plus the celestial aether) and the homocentric spheres of Aristotle, which he introduces in Part I, Chapter LXXII of the *Guide*, where he compares the unity of the universe to that of a living human being.

One of the issues raised by Maimonides was whether the world was created or eternal. He presents three theories: the Biblical belief that God had created the world out of nothing, the Platonic notion of creation from pre-existing matter, and the Aristotelian concept of the eternity of the cosmos. Maimonides defended the first of these views, the Mosaic *creatio ex nihilo*, which he presents in Part II, Chapter XIII of the *Guide*.

In the final chapters of the *Guide* Maimonides reiterates his aim, which is to explain how a man can attain the ultimate state of happiness through the perfection of his intellect so that he can contemplate the divine. ‘Having acquired this knowledge he will then be determined always to seek loving-kindness, judgment, and righteousness, and thus to imitate the ways of God. We have explained this many times in this treatise.’

Two Hebrew translations of *The Guide for the Perplexed* were done shortly after it was written, one by Samuel ibn Tibbon and the other by al-Harizi. During the next three centuries the *Guide* played a central role in Jewish philosophical discussions, with the followers of Maimonides vigorously defending his ideas against his detractors, some of whom wanted his books banned. As one group of his supporters proclaimed in defence of Maimonides: ‘The hearts of the people cannot be turned away from philosophy and the books devoted to it for so long as they have a soul in their bodies ... they intend to fight for the honour of the Great Rabbi and his books, and will dedicate their money, their offspring and their spirits to his holy doctrines as long as the breath of life is in their nostrils.’

The Guide for the Perplexed was translated into Latin in the thirteenth century and exerted a significant influence on the so-called Scholastic philosophy that was developing at that time, as is evident in the works of Thomas Aquinas. The *Guide* was still influential in western Europe as late as the time of Spinoza (1632–77), who, although he severely criticised Maimonides, agreed with his idea that perfect world peace could be achieved through reason, for this was how Spinoza thought that the messianic age would emerge.

Maimonides also wrote extensively on medicine, and at least ten of his medical works have survived, all of them written in Judeo-Arabic. He acknowledged his debt to Galen, as did all medieval physicians. Nevertheless, in several of his medical works he points out flaws in the writings of Galen, whom he also criticised for being ignorant in philosophy and theology.

Maimonides' attested medical works are the *Compendia of Galen's Books*, *Commentary on The Aphorisms of Hippocrates*, *Medical Aphorisms*, *On Hemorrhoids*, *On Asthma*, *The Regimen of Health*, *Treatise On the Causes of Symptoms*, a short untitled treatise on improving sexual performance, *Explanation of the Names of Drugs* and *On Poisons and Their Antidotes.*

The *Commentary on The Aphorisms of Hippocrates* is a collection of more than 400 brief statements on medicine attributed to Hippocrates. The first of the aphorisms, the best known by far, is 'Life is short, the art is long, time is limited, experience is dangerous, and judgment is difficult', which Maimonides applied to the medical profession, with its long years of training and the enormous number of complex subjects that had to be mastered.

The *Medical Aphorisms* was designed by Maimonides as a reference work for physicians, including some 1,500 topics that he chose 'from Galen's words' in 'all his books'. The book also includes material from six Arabic medical writers, along with occasional comments by Maimonides himself. The aphorisms deal with every aspect of medical practice and theory, including general rules of health, one of which is concerned with sexual intercourse. 'The indulgence in sexual intercourse is one of the requirements for the maintenance of health, providing there should be adequate [intervals] of abstinence between periods of indulgence, so that no noticable enfeeblement or weakness ensue; rather one's body should feel lighter than before the act. During the time one performs coitus, a person should not be filled with food, nor completely empty thereof, nor very cold nor very warm.'

The chapter devoted to Specific Remedies contains many bizarre substances, some of which were still part of the pharmacopeia of village folk-doctors in countries like Egypt and Turkey up until the beginning of modern times. One folk-remedy that he recommends has it that 'The brain of a camel, if dried, prepared in vinegar and imbibed, is of value against epilepsy.' Others are equally bizarre: 'Mouse excrement breaks bladder stones… If one boils a dung beetle in oil, and trickles the resultant oil into a [painful] ear, then the pain will subside immediately… A cattle hoof, if burned and drunk with oxymel, shrinks an enlarged spleen and stimulates the desire for coitus… Staring at the eyes of a wild donkey guarantees healthy vision, and helps against tearing of the eyes.'

The *Aphorisms* became a popular medical text, both in the Islamic world and in the Christian West, translated into both Hebrew and Latin, and it continued to be used in western Europe into the sixteenth century.

The treatise *On Hemorrhoids* was written for a young Muslim nobleman who suffered from this complaint, which Maimonides says usually results from an excess of black bile in the body. Maimonides advises against surgery, and recommends warm baths and bloodletting as treatments.

The treatise *On Asthma* was written for another young Muslim nobleman. Maimonides attributed asthmatic attacks to an emission of catarrh from the brain as well as fumes arising from the stomach. The regimen that he recommends to deal with these attacks includes proper diet, exercise, sleep, living conditions, bathing, massage and an avoidance of sexual intercourse. As regards medical practice in general, Maimonides says in this treatise that the 'art of medicine' depends on both 'experience and reasoning, and the things known by experience are much more numerous than those known through reasoning'.

The *Regimen of Health* was written for Prince al-Afdal, Saladin's eldest son, who had complained to Maimonides of his indigestion, constipation and attacks of depression. Only one of the four chapters of the book deals specifically with al-Afdal's complaints, but since his problems had to do with his general physical and mental health the regimen described in the other chapters also applied to his case. The proposed regimen was almost identical to that recommended in the treatise *On Asthma*, the additional advice being to treat al-Afdal's depression, for which he proposed music and pleasant conversation in the evening to relax him so that he would sleep soundly. The *Regimen* was popular among Muslims, Jews and Christians, and was translated from Arabic into Hebrew and Latin, with the Latin translation printed several times in the fifteenth and sixteenth centuries.

The *Treatise On the Causes of Symptoms* was also written for Prince al-Afdal, who still seemed to be suffering from the same complaints, in addition to hemorrhoids and a heart condition. The advice that Maimonides now gave him is an extension of what he had written in the *Regimen*, adding a cardiac medicine and recommending hot baths and poultices for his hemorrhoids. He also suggested that the Prince should reduce his sexual activity to once a day, either in the early evening before supper or at night after he had digested his meal. The *Treatise* was translated from Arabic into both Hebrew and Latin, and part of it was bound together with the *Regimen* and was published half a dozen times in western Europe in the fifteenth and early sixteenth centuries.

The short untitled treatise on improving sexual performance was written for another high-ranking Muslim, who had asked Maimonides for advice on increasing his sexual potency, which had deteriorated along with his general health. The man let Maimonides know that he did not want a difficult regimen, nor did he want to be told to be more moderate in his sexual activity, for he had a harem of young women to satisfy. Thus Maimonides limited his advice to matters of diet, mental attitude, massage, ointments and choice of sexual partners. He also prescribed an aphrodisiacal 'medication … beneficial for deficient erections, semen, and desire', which included fox testicles among its ingredients.

The *Explanation of the Names of Drugs* is a listing of 405 pharmaceutical items, with their names given in Arabic, Greek, Syriac, Persian, and Castilian, using information drawn from five Arabic writers.

The treatise on *Poisons and Their Antidotes* was commissioned by al-Qadi al-Fadil, Saladin's vizier. Aside from the antidotes, the advice that Maimonides gives is still used in the case of a poisonous snake bite, where a torniquet should be applied above the wound, incisions made, and the venom sucked out, while for ingested poisons vomiting should be induced. Among the antidotes is the famous 'electuary of Mithridates', which King Mithridates VI (r. 120–63 BC) is supposed to have taken throughout his life to immunise himself against poisons. The electuary, which was also used as a prophylactic and for other pharmaceutical purposes, remained popular in Europe up into the eighteenth century.

A work that is often attributed to Maimonides, though with some doubt, is a treatise entitled *The Inner Secret: A Memorandum for Noblemen, and Tried and True Devices for the Highborn*. This is a treatise on sexual matters dedicated to al-Muzaffer ibn Ayyub, King of Hamat in Syria, who was probably a cousin of Saladin's. Herbert A. Davidson writes that the author of this treatise 'concedes that one select class of human males benefits from sexual intercourse, men who have a hot, moist, irascible disposition, have hairy bodies, eat and drink heartily, live idle lives, and lack intellectual interests.'

The miscellaneous writings of Maimonides includes his extensive correspondence with fellow Jews in Egypt and elsewhere, among which are his legal *responsa*, answers to the queries sent to him regarding Jewish law. One particularly interesting response is his *Letter to the Scholars of Montpelier*, dated 1194 or 1195. This was a circular letter written in Hebrew, for those to whom it was addressed did not know Arabic. Its authenticity has been questioned, but present opinion seems to be that it was written by Maimonides. The letter was written in response to a query by a group of Jewish scholars in Montpelier concerning astrology, for they were reluctant to believe that a person's future was predetermined by the celestial configurations at the time of their birth, for this would make prayer and religious observance meaningless. Maimonides eased their fears, for his response is an unequivocal repudiation of astrology. 'Know, my masters, that every one of these things concerning judicial astrology that [its adherents] maintain – namely that something will happen one way and not another, and that the constellations under which one is born will draw him one way or another – all these assertions are far from being scientific; they are stupidity.'

His many letters reveal the admiration that Maimonides had for both ancient Greek and medieval Islamic philosophers, particularly Aristotle, Plato, al-Farabi, Ibn Sina and Ibn Bajja. He accepted Aristotelian physics for the terrestrial world, though not for the celestial realm, which he thought might be beyond human understanding. An even more difficult problem for him was the obvious contradiction between the Aristotelian astronomical model of the homocentric spheres and the mathematical Ptolemaic theory of epicycles, eccentrics, deferents and equants, and in his own thinking he did not accept any of the attempts by Islamic philosophers and astronomers that sought to resolve these questions.

Arabic sources rank Maimonides as one of the greatest physicians of all time, particularly because of his skill in treating ailments of both body and mind at the same time. He wrote in the *Misnah Torah* that everyone needs 'to make his body healthy and strong in order that his rational soul will be equipped for knowing God, inasmuch as it is impossible to understand and study the sciences when hungry or ill'. As an Arabic verse said in his praise: 'Galen's medicine is only for the body, but that of [Maimonides] is for both body and soul.'

Maimonides was not the only scholar to move from al-Andalus to the eastern Islamic world. The pharmacologist and botanist Ibn al-Baytar was born in Malaga ca. 1190 and studied in Seville. Around 1200 he crossed to the Maghrib and sailed from there to Asia Minor and Syria before settling in Cairo. While in Cairo Ibn al-Baytar served as chief herbalist under the Ayyubid sultan al-Kamil (r. 1218–38) and his son and successor al-Salih (r. 1240–49). Toward the end of his life he moved to Damascus, where he died in 1248.

Ibn al-Baytar's work in pharmacology is based on the writings of Dioscorides and Galen as well as those of his Arabic predecessors. His two best known works are *Al-Mughni*, which describes simple medicines used for various illnesses, and *Al-Jami*, an alphabetical list of some 1,400 medicines based on his own researches as well as those of his Greek, Persian and Arabic predecessors. Ibn al-Baytar's main contribution was his systemisation of the researches of Islamic scholars, who added between three and four hundred medicines to the thousand or so known since antiquity. His *Al-Jami* had considerable influence in the East, among both Muslims and Christians, for it was translated from Arabic into Armenian, but it was little known in the West.

The Ayyubid dynasty lasted until 1250, when the last sultan of that line was overthrown by the Mamluks, Turkish slaves who had come to dominate the Egyptian army. Eight years later the Mamluk sultan Qutuz routed the Mongols in a great battle in Palestine, the first major defeat suffered by the Central Asian nomads, who then retreated into Anatolia and never again directly threatened Egypt. On his return to Egypt, the Mamluk general Baybars murdered Sultan Qutuz and usurped the throne, beginning one of the longest and most illustrious reigns (1260–76) in the history of the Mamluk dynasty, which lasted until it was overthrown by the Ottoman Turks in 1517.

The court physician during the reign of Sultan Baybars was ‘Ala al-Din Ibn al-Nafis (ca. 1208–88), who was born in Transoxiana and studied medicine in Damascus. Besides being a physician, Ibn al-Nafis also lectured on jurisprudence at the al-Masruriyya School in Cairo. His importance as a physician, which led Muslims to call him the ‘second Ibn Sina’, was not fully recognised by western historians, for many of his medical writings were unknown until quite recent times. His *Comprehensive Book on the Art of Medicine*, in eighty volumes, which he wrote when he was in his thirties, was thought to have been lost until 1952, when one fragmentary volume was found in the Cambridge University Library. Three other volumes of this work were subsequently discovered in the medical library at Stanford University, one of them dated 1243–44. One of the interesting sections in these fragmentary remains concerns the surgical techniques used by Ibn al-Nafis, which he describes in minute detail, with examples of specific operations as well as discussions concerning the duties of surgeons and the relationships among doctors, nurses and patients.

The fame of Ibn al-Nafis stems from his discovery of the so-called minor circulation of the blood, i.e., between the heart and lungs. The fact that he had made this discovery was not known until 1924, when the Egyptian physician Dr Muhyo al-Deen Altawi discovered a manuscript of *Sharh Tashrih al-Qanun Ibn Sina* or Commentary on the Anatomy of Ibn Sina’s *Canon* an introduction to the work of Ibn Sina in which Ibn al-Nafis first describes the minor circulation of the blood.

> When the blood has been refined in the Right Ventricle, it needs be that it pass to the Left Ventricle where the Vital Spirit is generated. But between

> these two there exists no passage. For the substance of the heart there is solid and there exists neither a visible passage, as some writers have thought, nor an invisible passage which will permit the flow of blood, as Galen believed. But on the contrary the pores of the heart are shut and its substance there is thick. But this blood, after being refined, must of necessity pass along the Pulmonary Artery into the lungs to spread itself out there and to mix with the air until the last drop be purified. It then passes along the Pulmonary Veins to reach the Left Ventrical of the Heart after mixing with the air in order to become fit to generate the Vital Spirit. The remainder of the blood, less refined, is used in the nutrition of the blood. This is why there are between these two vessels (i.e., the Pulmonary Arteries and Veins), perceptible passages.

It is possible that European physicians first learned of the minor circulation through a translation of the work of Ibn al-Nafis by Andrea Alpago of Belluno (d. 1520). The first European to write about the minor circulation was Michael Servetus (ca. 1510–53), an Aragonese physician and theologian, who was condemned by Calvin for his unorthodox religious opinions and was burned at the stake in Geneva. The definitive theory of blood circulation was finally given by the English physician William Harvey (1578–1657), in his *Exercitatio Anatomica de Motu Cortis et Sanguinis*, published in 1628, which is generally considered to mark the beginning of modern medicine.

Ibn al-Nafis was followed by his student Ibn al-Quff (1210–88), who won renown as a surgeon and medical writer, his best-known treatise being *The Basic Work Concerning the Art of Surgery*. Ibn al-Quff is widely credited (though this has been disputed) with being the first to discover the existence of capillaries and their role in blood circulation.

The first European scientist to make this discovery was Marcello Malpigi of Bologna (1628–94), who in 1661 used a microscope to detect capillaries and explain their role in circulating blood between the arteries and veins. Ibn al-Quff, in giving an anatomical description of the heart, writes that

> The heart has four outlets of which two are on the right side. The one branching from the Vena Cava, carries the blood. In the orifice of this blood vessel – which is thicker than any of the other openings – there are three valves which close from the outside in. The second is connected with the arterial vein and through it nourishment from the lungs come. I, heretofore, know of no one ever describing it.

Two fourteenth-century physicians emerged from Mamluk Cairo: Shams al-Din al-Akfani and Sadaqah ibn Ibrahim al-Sadhili. Al-Akfani composed a pioneering work on first aid entitled *The Refuge of the Intelligent* *during the Absence of the Doctor.* Al-Sadhili wrote on opthalmology, the last work on medical scholarship carried out in Cairo under the Mamluks.

Both Cairo and Damascus continued to be centres for astronomy throughout the Mamluk period. The leading Mamluk astronomers were usually *muwaqqits*, or time-keepers, who were employed by mosques and madrasas to calculate the astronomically-determined times of the five daily prayers as well as possibly the days of the beginning and end of the holy month of Ramadan (though this has never been proven). The extant Mamluk manuscripts include treatises in all five fields of medieval astronomy: geometrical models of the motions of the sun, moon and planets; mathematical theories to predict the positions of the celestial bodies in order to produce *azyaj*, or astronomical tables; astronomical time-keeping using spherical trigonometry; the science of astronomical instruments, principally the astrolabe, quadrant and celestial sphere; and compound instruments. Among those who worked in these fields in Mamluk Cairo and Damascus was the fourteenth-century astronomer Ibn al-Shatir, whose mathematical theory of planetary motion was used in part and alongside other models by Copernicus.

CHAPTER 10

Ingenious Mechanical Devices

One of the most illustrious figures in the history of Islamic mathematics is Abu'l Fath Umar ibn Ibrahim al-Khayyami (ca. 1048–ca. 1130). As his name indicates he was the son of Ibrahim al-Khayyami, whose last name means 'the Tentmaker'. Thus in the West, where he is more famous as a poet than as a mathematician, he came to be known as Omar Khayyam, the 'Tentmaker'.

Al-Khayyami was born in Nishapur soon after the Seljuk Turks conquered much of the 'Abbasid empire, reaching the pinnacle of power by their capture of Baghdad in 1055. One of his teachers was the philosopher Bahmanyar, who had been a student of Ibn Sina. By his own testimony, al-Khayyami also studied the writings of Ibn al-Haytham, al-Khazin, al-Buzjani, al-Farabi, Ibn Sina and other renowned Islamic scholars, as well as the works of Aristotle, Archimedes, Euclid, Apollonius and Ptolemy.

But apparently the conditions under which al-Khayyami lived early in his career were so precarious that he had little time to study and do research, as he notes at the beginning of his *Demonstration of Problems of Algebra*: 'I was unable to devote myself to the learning of this *al-jabr* [algebra] and the continued concentration upon it, because of obstacles in the vagaries of Time which hindered me; for we have been deprived of all the people of knowledge save for a group, small in number, with many troubles ...'

Nevertheless, during this difficult early period of his life al-Khayyami was able to write two treatises on mathematics, one of them a treatise entitled *Problems on Arithmetic*, now lost, as well as a short work on the theory of music.

Around 1070 al-Khayyami settled in Samarkand, where under the patronage of the chief justice Abu Tahir he wrote his great treatise on the *Demonstration of Problems of Algebra*, which he had been planning for some time.

Then, at the invitation of the Seljuk sultan Jalal al-Din Malikshah and his vizier Nizam al-Mulk, al-Khayyami was invited to Isfahan, where in 1074 he was appointed court astrologer and director of the royal observatory. He remained in Isfahan for eighteen years, during which time he completed a supplement to his treatise on algebra, while he also directed a programme of calendar reform that included the compilation of a set of astronomical handbooks with tables called the *Zij Malikshahi*.

Malikshah's third son Sanjar succeeded to the throne in 1118 and moved the capital of the Seljuk sultanate to Marw in Khorasan. Al-Khayyami moved from Isfahan to Marw and joined the sultan's court, which became a centre of Islamic learning. During his years in Marw, al-Khayyami wrote a number of treatises in mathematics, philosophy and mechanics, the latter works done in collaboration with his disciple al-Khazini. His contemporary al-'Arudi al-Samarqandi says that he met al-Khayyami at Balkh in AH 506 (1112–13 AD).

Al-Samarqandi goes on to say that al-Khayyami died in his native Nishapur in AH 526 (1131 AD), when he would have been around eighty-three.

Al-Khayyami's *Demonstration of Problems of Algebra* was for many years – until the publication of a work by Sharif al-Din Tusi, which went beyond al-Khayyam's research – considered to be the culmination of Islamic research in this field, going beyond that of al-Khwarizmi to include cubic equations. He points out at the beginning of his treatise that he is breaking new ground in mathematics. 'One of the mathematical notions needed in the part of philosophy known as mathematics is the art of Algebra, which has been invented in order to determine the numerical and the geometrical unknowns. And it contains species... whose solution has been impossible for most of those who examined them. As for the Ancients, no statement about these has come down to us from them.'

In his treatise on algebra al-Khayyami uses both arithmetic and geometric methods to solve quadratic equations, employing a scheme of intersecting conics to solve cubic equations, an approach first taken by Archimedes and later by Ibn al-Haytham. As al-Khayyami wrote in this regard: 'Whoever thinks algebra is a trick in obtaining unknowns has thought it in vain. No attention should be paid to the fact that algebra and geometry are different in appearance. Algebras are geometric facts which are proved.'

Al-Khayyami refers to his lost work on arithmetic in his treatise on algebra, where he refers to what he calls the Hindu methods for finding fourth, fifth, sixth and higher powers of a binomial.

> I have written a book to prove the validity of those methods and to show that they lead to the required solutions, and I have supplemented it in kind, that is, finding the square of the square, and the qudrato-cube, and the cubo-cube, however great they may be; and no one has done this before; and those proofs are only algebraic proofs based on the part of the book of the *Elements.*

Al-Khayyami is apparently referring to the triangular array of the binomial coefficients generally known as Pascal's triangle, which was presented by al-Kharaji in the eleventh century, by al-Samaw'al in the twelfth century, by the Chinese mathematician Yang Hui in the thirteenth century, by Petrus Appianus and Niccolo Tartaglia in the sixteenth century and in 1655 by Blaise Pascal.

Another important mathematical thesis by al-Khayyami is his *Commentary on the Difficulties of Certain Postulates of Euclid's Work*, which he completed toward the end of 1077. This is divided into three books, the first dealing with the theory of parallel lines, the second with the concepts of ratio and proportionality, and the third with the compounding of ratios.

Al-Khayyami's plan for calendar reform is known only from references to it in the astronomical tables of Nasir al-Din al-Tusi. The system, known as the Jalali calendar, was presented to Sultan Malikshah ca. 1079 and was used throughout the Seljuk era, which ended in the thirteenth century. It was used in astronomical handbooks for centuries and then officially reintroduced in 1925 by Reza Shah Pahlavi as the calendar of Iran. It is still used in Iran and in the central Asian republics, as well as in the Kurdish areas of other countries in the region.

The Jalali calendar begins on the day after the vernal equinox and ends on the day of the next vernal equinox, except on leap years, when an intercalary day is added periodically to correct for accumulated error. There are eight leap years in every cycle of thirty-three years, with an extra day in years 4, 8, 12, 16, 20, 24, 28 and 33. This makes the average length of the year 365.2424 days, a difference of 0.0002 days from the astronomical calendar, amounting to an error of one day in 5,000 years. By way of comparison, the modern Gregorian calendar, which was first used in 1582, has an average year length of 365.2425 days, giving an error of one day every 3,333 years.

Al-Khayyami refers to his calendar in one of the quatrains of his *Rubaiyat*, first translated into English in 1859 by Edward Fitzgerald, perhaps the best evidence that these poems were actually written by him:

Ah, but my Computations, People say
Reduced the year to better reckoning? – Nay,
'Twas only striking from the Calendar
Unborn Tomorrow, and dead Yesterday.

Al-Khayyami also wrote two treatises on mechanics, both of them concerned with the use of scale balances in weighing objects accurately. The first is entitled *The Book of the Balance of Wisdoms, On the Art of Defining Quantities of Gold and Silver in a Body Consisting of Both*, in which he determined the specific weights of the two substances by weighing them in both air and water, a method first used by Archimedes. The second is entitled *On Right Balance*, about the use of a scale balance with movable weights. Both of these treatises were included in a work by al-Khayyami's follower Abu'l Fath 'Abd al-Rahman al-Khazini entitled *Kitab mizan al-hikma*, or *The Book of the Balance of Wisdom*, completed in 1121–2, his best-known work, which has been described as 'One of the most remarkable books on mechanics, hydrostatics, and physics of the Middle Ages'.

Al-Khazini flourished in Marw during the years ca. 1115–30. Originally a slave-boy of Byzantine origin, possibly a eunuch, he seems to have been a high government official under the Seljuk sultan Sanjar (r. 1118–57), during which time Marw became a centre of literary and scientific activity.

The word *mizan* in the title of al-Khazani's book comes from the Arabic word for 'justice' in the sense of equipoise, as in the weights in equilibrium on a balance, described by al-Khazini in his introduction:

> This just balance is founded upon geometrical principles and deduced from physical causes, in two aspects: 1) as regards centers of gravity, the most elevated and noble division of the mathematical sciences, which is knowledge that the weights of heavy things differ according to the distance they are placed from a fulcrum – the foundation of a steelyard; and 2) knowledge that the weights of heavy things differ according to the rarity or density of the fluids in which the thing weighed is immersed – the foundation of the *mizan al-hikma*.

The Book of the Balance of Wisdom is an encyclopedia of medieval mechanics and hydrostatics, including commentaries on the writings of earlier scholars from Euclid and Archimedes to Thabit b. Qurra al-Biruni and al-Khayyami. The topics covered in the encyclopedia include theories of the lever and the concept of centre of gravity; measurements of specific gravities of fifty substances, including both liquids and solids; determination of the constituents of alloys; the mechanisms of the steelyard and other balances, including that of al-Khayyami and one attributed to Archimedes, and the measurement of time using a clepsydra, or water-clock.

One of the water-clocks described by al-Khazini, known as the Universal Balance, had a steelyard balance in which the outflow clepsydra was suspended on the end of the short arm, while hanging from the graduated long arm there were two weights, one large and the other small. As the water flowed out the two weights were adjusted to maintain equilibrium, with the position of the large one giving the hour of day and the small one the minutes. The encyclopedia also establishes standards of measurement, discusses capillary action and describes ingenious mechanical *automata*.

Al-Khazini was also a distinguished astronomer. His most important work in this field was the *Sanjar Zij*, the astronomical tables he compiled for Sultan Sanjar, which also includes interesting information on various calendars as well as lists of religious holidays, fasts, rulers and prophets, concluding with tables of astrological quantities. Another of his writings on astronomy is a *Treatise on Instruments*. This is in seven parts, each devoted to an astronomical instrument, with instructions for its use as well as explanations of its geometrical basis.

Another Greek scientific tradition that flourished in late medieval Islam was the making of *automata*. Islamic work in this field culminated with the inventions of Badi al-Zaman Abu'l-Izz Ismail ibn al-Razzaz al-Jazari (fl. ca. 1200), following in the tradition of Ctesibus and Hero of Alexandria and Philo of Byzantium, as well as that of the Banu Musa. Badi al-Zaman means 'Prodigy of the Age', which he was indeed, while al-Jazari refers to his homeland, al-Jazira, or Mesopotamia.

Al-Jazari's only extant work, *The Book of Knowledge of Ingenious Mechanical Devices*, translated and annotated by Donald R. Hill, was published in 1974. Hill's introduction to Banu Musa's work on *automata*, which he translated and annotated, gives a summary of the Banu Musa's inventions, 100 in number. These include fountains, self-trimming oil-lamps, an automatic musical instrument, a 'gas mask' for use in polluted wells, a mechanical claw for excavating in river beds and trick vessels for dispensing liquids, the latter comprising eighty per cent of the total. According to Hill:

> In design and operation these are very similar to the devices described by Philon and Heron, and are certainly derived from these. Use is made of pipes, jacketed siphons, cone-valves, taps and air-holes; many of the devices are quite ingenious. The main difference between the Banu Musa devices and those described by the Greek writers, apart from the greater complexity of the former, is that the Banu Musa make use of properly fitted cone-valves, whereas Philon and Heron mention only crude clack-valves and plate valves.

All that is known of the life of al-Jazari comes from his own statement in the introduction he wrote for his work. There he says that when he wrote the book he was in the service of Nasir al-Din, the ruler of the Turcoman Artukid emirate. He notes that he had been in the service of the emir's family for twenty-five years, beginning in AH 577 (1181–2 AD), which means that his book was completed ca. 1206. He tells of how the emir asked him to write the book after he had presented him one of his mechanical devices:

> I was in his presence one day and had brought him something which he had ordered me to make. He looked at me and what I had made and thought about it, without my noticing it. He guessed what I had been thinking about, and unveiled unerringly what I had concealed. He said 'you have made peerless devices, and through strength have brought them forth as works; so do not lose what you have wearied yourself with and have plainly constructed. I wish you to compose me a book which assembles what you have created separately, and bring together a selection of individual items and pictures.'

Al-Jazari goes on to say that his book describes fifty devices, which he calls specimens, each of which makes up a separate chapter. These are divided into six categories, with ten chapters in each of the first four and five each in the fifth and sixth. The book has 173 illustrations, ranging from rough sketches and mechanical drawings to miniature paintings.

Category I is 'On the construction of clocks from which can be told the passage of the constant and solar hours by means of water and candles.' The ten devices in this category are the castle water-clock, the water-clock of the drummer, the water-clock of the boat, the elephant water-clock, the beaker water-clock, the water-clock of the peacocks, the candle-clock of the swordsman, the candle-clock of the scribe, the monkey candle-clock and the candle-clock of the doors.

Al-Jazari describes these clocks in minute detail, as for example in the chapter on the castle water-clock, which is divided into ten sections, the first of which, the Introduction, describes the appearance and operation of the device, in which he says he 'followed the method of the excellent Archimedes'.

As al-Jazari describes the clock, which is in the form of a castle doorway: 'Above the door, in a lateral straight line, are 12 doors, each of which has two leaves which are closed at the beginning of the day. Below these, and parallel to them are 12 [more] doors, each with one leaf, which all have the same colour at the beginning of the day. Below the second set of doors is a frieze projecting one fingerbreadth from the edge of the wall.' He goes on to say that a crescent moon moves along the ledge in front of the doors. On either side of the wall below the ledge, a bird with outstretched wings stands in a niche, and below each of them is a vase containing a cymbal. Between the two niches are 12 glass globes arrayed around the arch of the castle doorway. Below there are the figures of two drummers, two trumpeters and a cymbalist. Above the castle doorway there is a semicircle whose periphery is decorated with 6 of the 12 zodiacal signs, those visible at any time, and below them are spheres representing the sun and moon.

At the beginning of the day the crescent moon moves along the frieze, and as it does so various figures appear in the upper doors while the lower doors change colour. At the same time each of the two birds drops a ball from its beak onto the cymbal in the vase below 'and the sound is heard from afar'. He goes on to say that 'This happens at the end of every hour until the sixth, at which time the drummers drum, the trumpeters blow and the cymbalist plays his cymbals for a while. This occurs also at the ninth and twelfth hour.' Meanwhile the spheres representing the sun and moon show their positions among the signs of the zodiac, the lunar sphere also exhibiting the cyclical phases of the moon.

After the Introduction, the successive sections of Category I are entitled: The water-reservoir; Construction of the flow regulator; Installation of the instruments; Device of the circle for the outflow of water; On the place in which the apparatus is installed and the functioning of the instruments; On the means for imparting motion to all the things mentioned so far; On the means for imparting movements to the hands of the drummers and the cymbalist, and the sound for the trumpeters; Construction of the spheres of the zodiac, the sun and the moon.

Chapter 7 of Category I describes the candle-clock of the swordsman. Al-Jazari says in his introduction to this chapter that 'I have never come across a work by anyone on candle-clocks and have never seen a completed [example of such a] clock.' He then describes the appearance of his candle-clock, a tall brass candle-holder of fine workmanship, upon which is a brass sheath.'

> Near its foot is a falcon erect up a perch. Its back and the back of its head are against the sheath and its wings are outspread. Towards the top of the sheath is a bracket projecting about the length of a finger from the sheath and on this is a black slave. His legs are hanging down and in his right hand is a sword, [held] against his chest. His left hand is on the bracket. On the candle, towards its tip, is a cap, hollow underneath, with the wick projecting from it.

He then goes on to describe how the clock marks the passage of the hours during the night:

> The wick is lit at nightfall, and part of it is burned away, [another] rises to take its place. When a constant hour has passed the falcon lets fall a ball from its beak on to the floor of the pedestal of the candle-holder, and the slave strikes the wick with his sword, removing the portion that has burned away, and so for every hour till morning. The passage of the hours of the night can be told from the number of balls.

Category II is 'On the construction of vessels and figures suitable for drinking sessions.' The ten chapters in this category describe various trick vessels and *automata* designed to amuse the emir and his boon companions at their drinking sessions. The first of these is described by al-Jazari as 'a goblet that arbitrates at drinking parties', i.e., decides which of the guests will take the next drink, making sure that he finishes it.

As al-Jazari describes it, the goblet, made of silver or brass, stands on a tall pedestal and is covered by a fretted lid with a dome surmounted by a bird with an open beak. The steward brings the goblet into the dining-room and sets it down in the middle of the assembly. Then he pours the wine slowly on to the lid, letting it flow through the fretwork. As he does so the bird rotates and emits a shrill whistle until the vessel is nearly full, whereupon he stops pouring. The bird comes to rest and stops whistling: its head is pointed toward one of the party, to whom the steward hands the goblet. The guest drinks from the goblet and when he is finished he hands it back to the steward. But if there is any wine left in the goblet the bird whistles and the steward does not accept the glass but tells the guest to drink what is left. Only when all the wine is emptied does the bird remain silent, in which case the steward will take the goblet. Al-Jazari assures us that even 'If a mere 5 *dirhams* remain in it the bird will whistle. This will happen even if a hundred sips are taken from the goblet without emptying it completely.'

Category III is 'On the construction of pitchers and basins and other things for hand-washing and phlebotomy.' Seven of the ten chapters in this category describe pitchers or basins used by the emir and his guests for washing their hands before dinner parties, while the other three are descriptions of basins used in phlebotomy, or blood-letting. The most famous of the first type is the Peacock Basin, which al-Jazari describes in chapter 9. The basin took its name from a mechanical peacock that spouted water from its beak when one of the emir's guests stood before it to wash his hands, with the figure of a slave emerging to offer some powdered soap, after which another mechanical slave held out a towel so that he could dry his hands.

Chapter 5 of Category III is a description of one of the devices designed by al-Jazari for use in phlebotomy, in which the amount of blood taken from the patient is measured accurately and displayed on a graduated scale. The device is a deep circular basin with a flat rim. In the centre is a platform on which there is the figure of a monk holding a staff whose end rests on the rim of the basin whose periphery is marked with numbers ranging from zero to 120. As blood is taken from the patient it flows into the basin and raises the level of the platform. As it does so the platform rotates, causing the end of the monk's rod to move along the graduated scale and measures the volume of blood. 'And so on up to 20 *dirhams* and 30 *dirhams* up to 120 *dirhams*, according to the quantity to be extracted from the patient.'

Category IV is 'On the construction in pools of fountains that change their shapes at known intervals, and of machines for the perpetual flute.' Six of the ten chapters in this category deal with fountains that change their shape at regular intervals, such as varying the number and shape of their jets, while the other four describe devices in which a tube of water is made to play like a flute. All of these devices make use of so-called tipping-buckets, containers that tip over when they are full and discharge all of the water they contain into a tank.

Chapter 1 describes one example of the first type of fountain: 'It is a fountain in a pool: the water shoots up from it in a single vertical jet for the space of one constant hour, then it changes and shoots up for the space of an hour in six curving jets. Then it changes and emits a single jet, and so on, for as long as the water flows into it.'

In Chapter 7 al-Jazari describes a flute-playing device: 'It is an instrument for a perpetual flute with two spheres, one of whom is silent while the other blows, then the one who was blowing falls silent and the one that was silent blows. Also the flautist plays continuously on the pool, [where] there are figures of various types of musicians.'

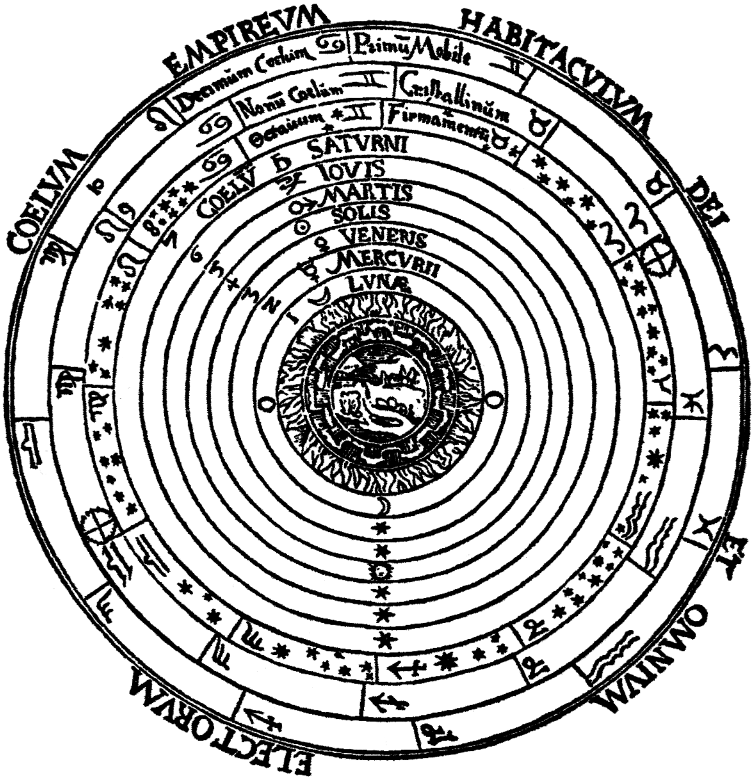
Category V is 'On the construction of machines for raising water from pools, and from wells which are not deep, and from running streams.' One of these, described in Chapter 3 and illustrated with a miniature, shows the wooden figure of a cow, which moves around the periphery of a copper disk turning two sets of gears, one of which turns a wheel that has two ropes on it carrying jars. As al-Jazari describes it: 'The ropes go over the back of the wheel and are immersed in the water of the pool in the usual manner. The water discharges from the jars into an irrigation channel inside the wheel, and the water runs there from wherever is desired.' He goes on to say that the machine 'is beautiful to behold, with upper wheels, splendid craftsmanship, elegant shapes, and handsome design. The ropes are silken, the jars delicate and painted with various colours, as are the wheels, the cow and the disc.'

Category VI is 'On the construction of miscellaneous devices.' One of the most interesting of these is in Chapter 3, which describes 'A lock for locking a chest by means of 12 letters of the alphabet.' This is the earliest-known example of a combination lock, which first appears in England early in the seventeenth century. As Donald R. Hill notes: 'It is interesting to observe that the wheels in the Butterworth combination lock (about 1846 AD) are strikingly similar to the discs used by al-Jazari.'

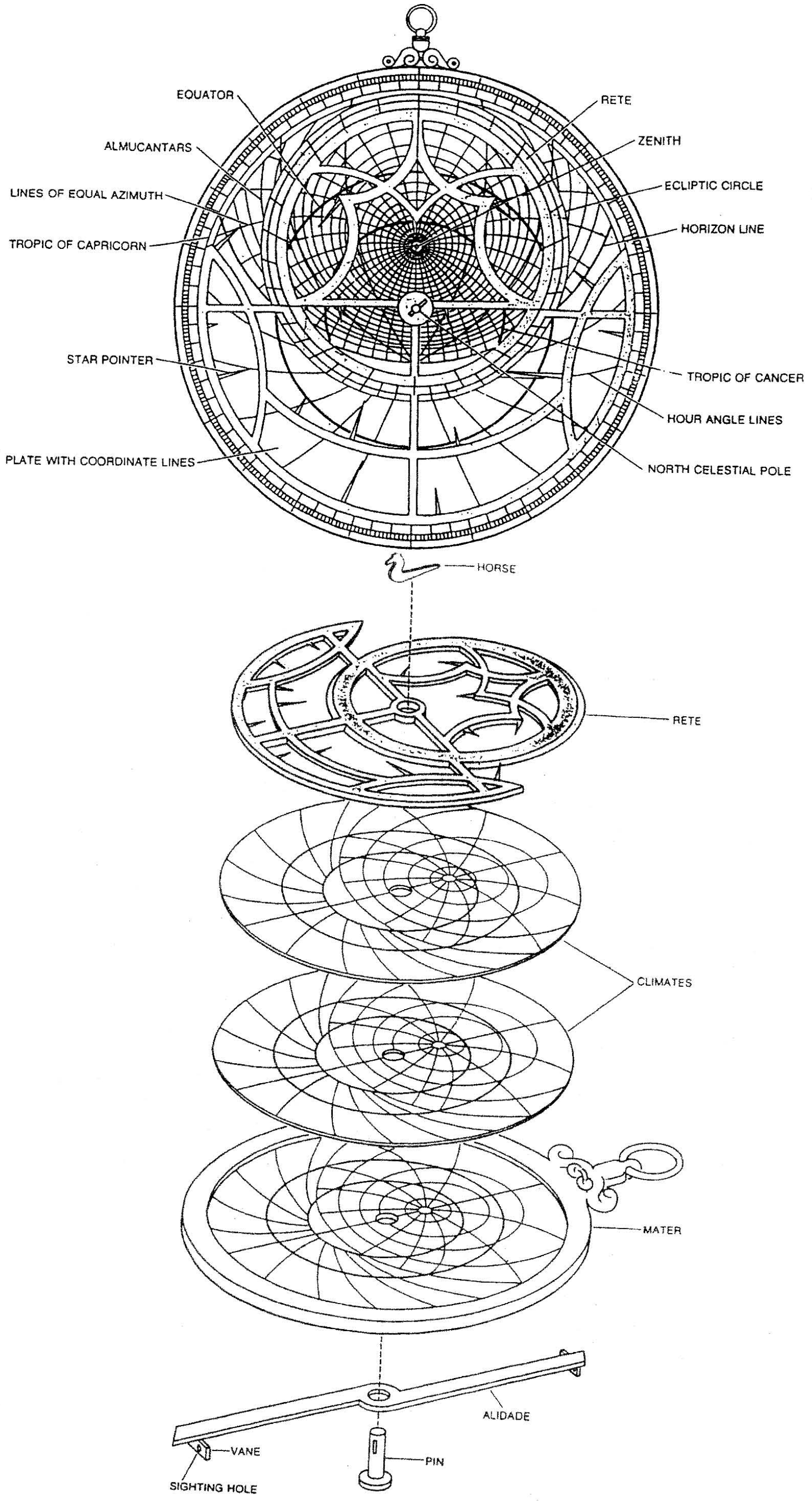
Another interesting *automata* appears in Chapter 5, where al-Jazari describes the operation of an *automata* that may be the world's first alarm clock. The device is in the form of a brass boat, in the middle of which there is the standing figure of a sailor holding an oar with his left hand while his right hand holds a flute to his lips. A hole in the bottom of the boat allows water to leak in so that in exactly one hour it will be submerged, at which point the sailor's flute emits a loud whistle. This awakens the owner if he is sleeping, as al-Jazari explains: 'If the observer forgets about it, it may sink without him noticing, so he does not know how much time is elapsed. So I made this device so that he will know from the pipe that the boat has sunk, and will wake from his doze at the sound.'

In the conclusion to his edition of *The Book of Knowledge of Ingenious Mechanical Devices*, Hill describes it as 'one of the earliest manuals of engineering practice that has come down to us.' He goes on to say of al-Jazari that 'He was a master craftsman, fully conversant with all branches of his trade, consciously proud of his membership in the technical fraternity. More rarely, he was a master craftsman who could write, and who has left us an engineering document of the first importance.'

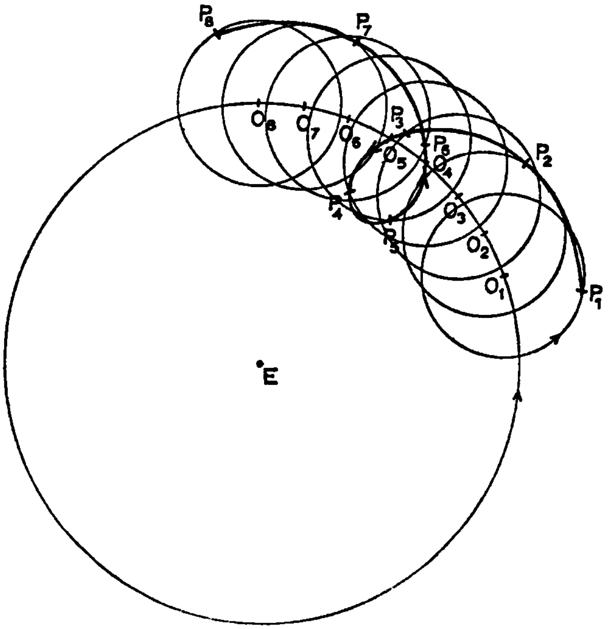
Some of his inventions later reappeared in the West, including his conical valve, mentioned by Leonardo da Vinci, and patented in England in 1784, more than five centuries after it had been made by al-Jazari as part of one of his ingenious mechanical devices.



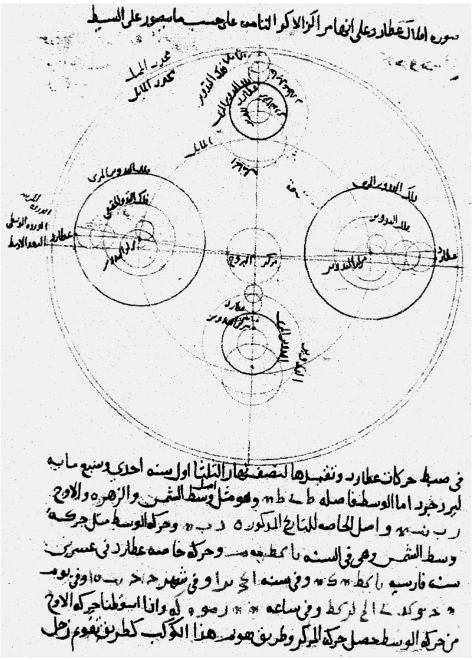
Aristotle's Cosmology. From Petrus Apianus, *Cosmographia per Gemma Phrysius restituta*, Antwerp, 1539



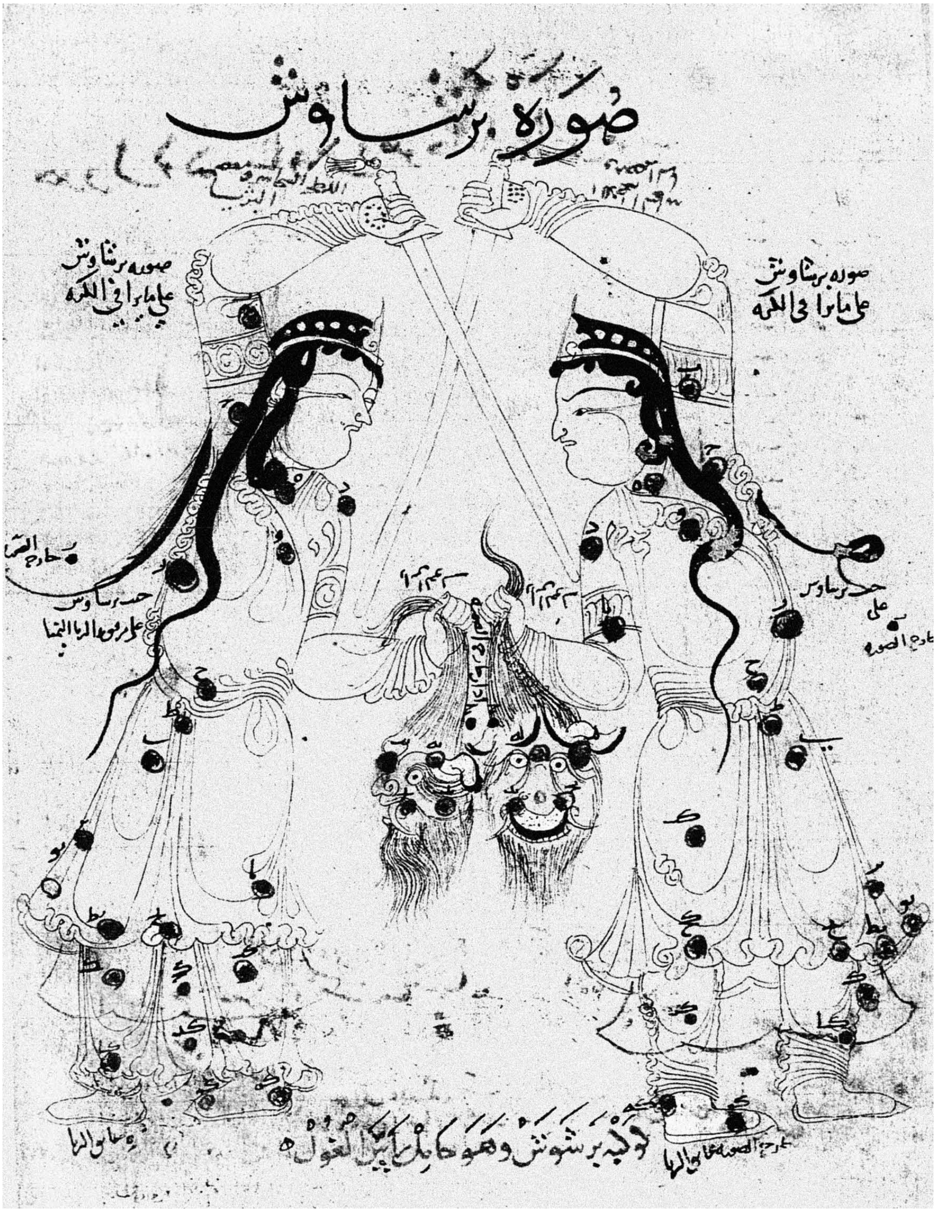
The Astrolabe



Eudoxus’ epicycle theory of planetary motion



Ibn al-Shatir’s model for the orbit of Mercury using multiple epicycles



The constellation Perseus from Al-Sufi's
Book of the Fixed Stars (The British Library)

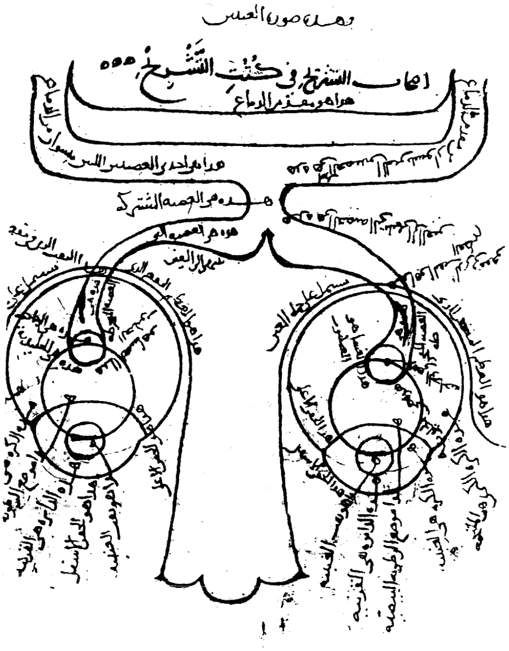


Diagram of the eye and related nerves, from an eleventh-century manuscript of Ibn al-Haytham’s *Book of Optics*

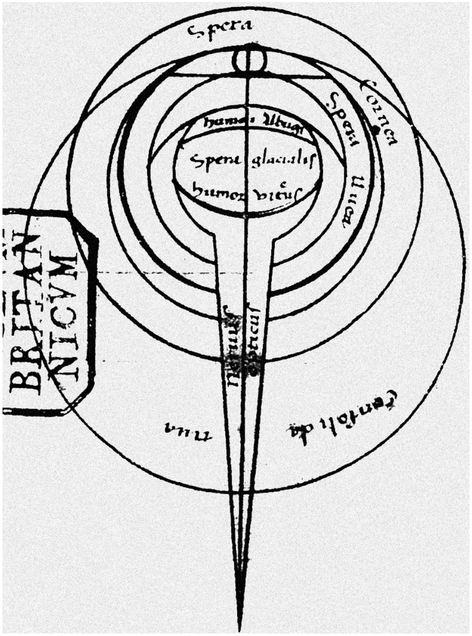
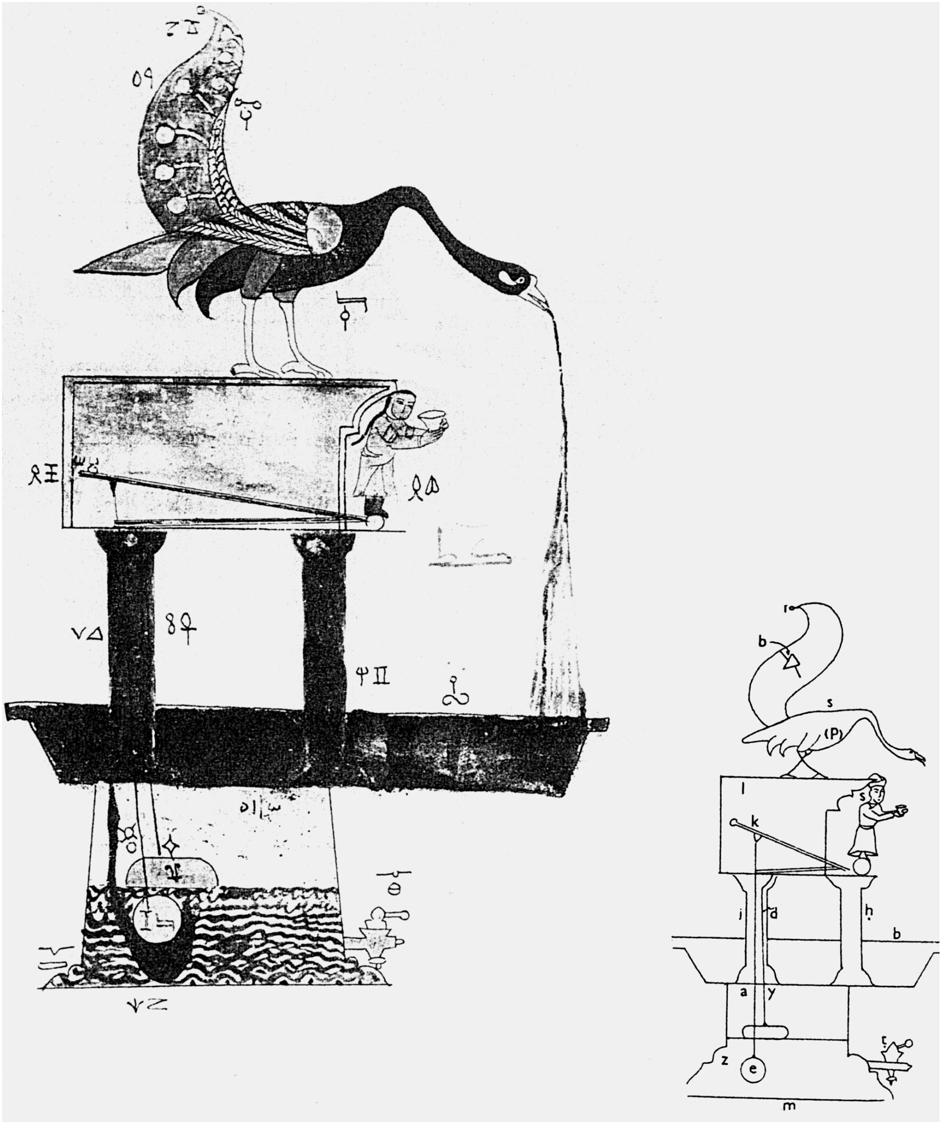
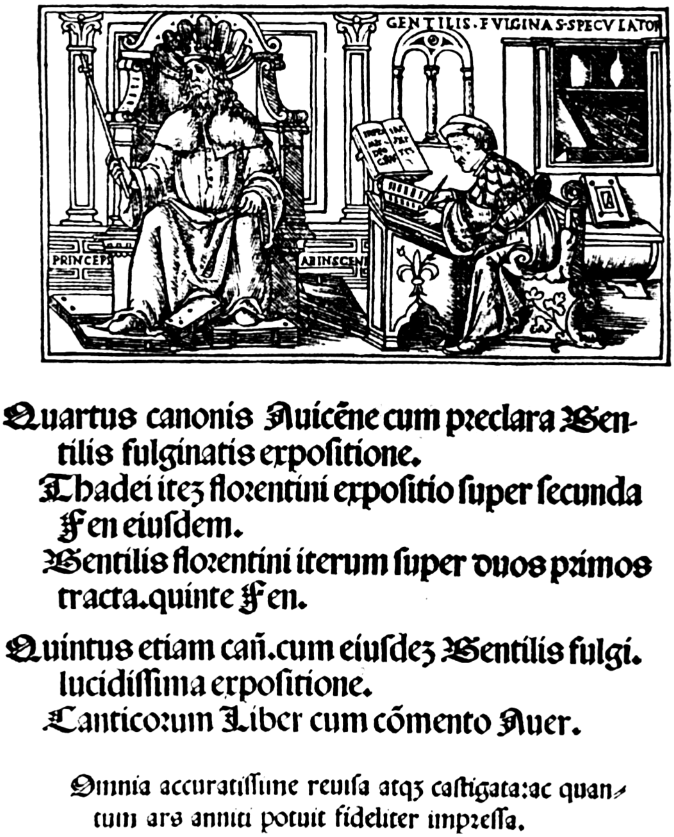


Diagram of Ibn-al Haytham’s theory of vision, from a fourteenth-century Latin version of his *Book of Optics*



The Peacock Fountain, from Al-Jazari's *Book of Ingenious Mechanical Inventions* (Boston Museum of Fine Arts, Boston, Golubew Collection)

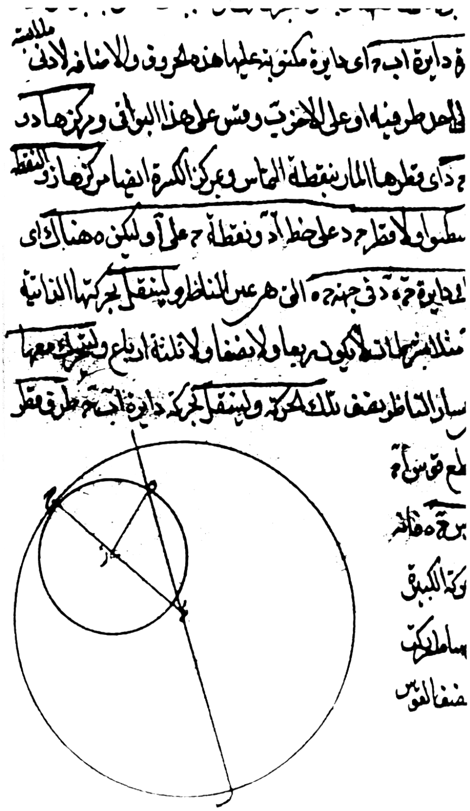


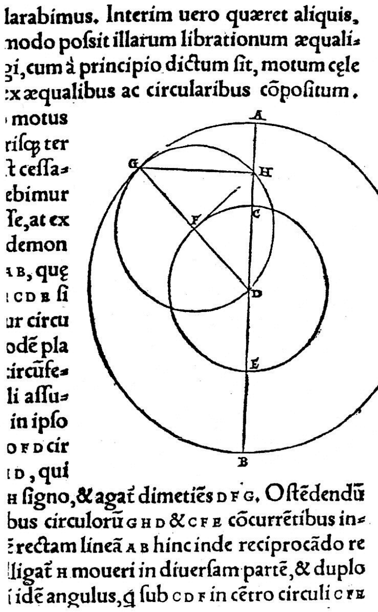
Quartus canonis Auicēne cum preclara Gentilis fulginatis expoſitione.
Thadei iteꝫ florentini expoſitio ſuper ſecunda Fen eiuſdem.
Gentilis florentini iterum ſuper duos primos tracta. quinte Fen.

Quintus etiam cañ. cum eiuſdeꝫ Gentilis fulgi. lucidiſſima expoſitione.
Canticorum Liber cum cōmento Auer.

Omnia accuratiſſime reuiſa atqꝫ caſtigata: ac quantum ars anniti potuit fideliter impreſſa.

Page from the sixteenth-century Latin translation of the *Canon of Medicine* by Ibn Sina (Avicenna)




larabimus. Interim uero quæret aliquis,
nodo poſsit illarum librationum æquali-
gi, cum à principio dictum ſit, motum cęle
:x æqualibus ac circularibus cōpoſitum.
motus
riſq; ter
t ceſſa-
ebimur
ſe, at ex
demon
A B, quę
C D B ſi
ur circu
odē pla
circūfe-
li aſſu-
in ipſo
D F D cir
I D, qui
H ſigno, & agat dimetiēs D F G. Oſtēdendū
bus circulorū G H D & C F E cōcurrētibus in-
rectam lineā A B hinc inde reciprocādo re
ligat H moueri in diuerſam partē, & duplo
idē angulus, q ſub C D F in cētro circuli C F E

Nasr al-Din Tusi and Copernicus

left: Diagram illustrating the ‘al-Tusi couple’, from a fifteenth century Arabic commentary on the *Compendium of Astronomy* by Nasir al Din al-Tusi

right: Diagram illustrating planetary motion, from *De Revolutionibus* by Copernicus.

CHAPTER 11

Islamic Technology

Much of the Islamic legacy in science is preserved in manuscript collections around the world, particularly in countries that were and continue to be centres of Muslim culture, though many manuscripts are also found in Europe as well as the United States and India. Among the manuscripts that are preserved in these libraries are a number of works on technology, part of the Islamic legacy that has been to some extent overlooked by historians, though it transformed society not only in the medieval Muslim world but in the Christian West as well.

The most authoritative modern work on this subject is *Islamic Technology, An Illustrated History*, by Ahmad Y. al-Hassan and Donald R. Hill. The authors note that 'historians have acknowledged the progress achieved by Muslim scientists in mathematics, astronomy and the exact sciences, but they have for the most part been harsh in their judgment on Islamic technology'. They go on to point out the important role that technology played in Islamic civilisation, particularly during the golden age in Baghdad and al-Andalus. 'When people speak of the splendour of Granada or Baghdad, they are referring in fact not only to their artistic grandeur, but also to the high level of their technology.'

The cover of their book has a miniature from al-Jazari's *Book on the Knowledge of Ingenious Mechanical Devices*, one of the manuscripts that I viewed in the library that is housed in a former madrasa of the Süleymaniye mosque in Istanbul. The miniature is an intricate drawing in coloured inks showing a water-raising device known as a *saqiya*, an animal-powered machine that originated in the Roman era and was used for irrigation throughout the medieval Islamic world. Al-Hassan and Hill describe the operation of the *saqiya* in detail and point out that ‘It is still in limited use today in the Muslim world and in the Iberian peninsula and the Balearic islands.’ And indeed in the early 1960s I saw animal-powered *saqiyas* in use in both Turkey and Egypt, though the devices are probably now powered by gasoline engines.

Their book has chapters on mechanical engineering; civil engineering; military technology; ships and navigation; chemical technology; textiles, paper and leather; agriculture and food technology; mining and metallurgy; engineers and artisans; with discussions of the historical issues in the introduction and epilogue, including a section on the transfer of technology from the Islamic world to the West. The latter section cites examples of Arabic words that entered English and other European languages through the introduction of Islamic technology.

> To cite but a few examples: in textiles – muslin, sarsanet, damask, taffeta, tabby; in naval matters – arsenal, admiral; in chemical technology – alembic, alcohol, alkali; in paper – ream; in foodstuffs – alfalfa, sugar, syrup, sherbet; in dyestuffs – saffrons, kermes; in leather working – Cordovan and Morocco. As one would expect, Spanish is particularly rich in words of Arabic origin. We have, for example, *tabona* for a mill, *acena* for a mill or water-wheel, *acequia* for an irrigation canal.

The *saqiya* is only one of a number of water-raising devices developed by medieval Islamic technology, others being the *shaduf* and the *noria*, both of which originated in antiquity.

The *shaduf* is a simple wooden lever, with a stone counterweight at one end and a bucket at the other, with the fulcrum placed to give a two to one ratio in lifting the water. I have seen *shadufs* used in Turkey in the early 1960s, and I would guess they are still used in Egypt and Iraq, where they were probably invented at the beginning of the neolithic agricultural revolution some ten millennia ago.

The *noria* is a huge water-wheel driven by a fast-flowing stream, in which buckets on the periphery of the wheel carry water up to a head tank connected to an aqueduct. The earliest description of the *noria* is by Vitruvius in his *De architectura* (*The Ten Books on Architecture*) written in the first century BC, in which he notes that there were many of them in Iran. The earliest reference to the *noria* in Islamic sources is by Ibn Qutayba (d. 889), in his *Adab al-Katib* (*Education of the Secretary*).

The geographer al-Idrisi, writing in 1154, describes a *noria* that was part of the water-supply system in Toledo. Al-Hassan and Hill note that ‘Although the machine is now rarely used in practice, some fine examples can still be seen, notably on the River Orontes at Hama in Syria.’ In 1998

I saw a beautifully restored *noria* operating in Lijiang, an ancient town in Yunnan province in south-west China. Hill, in his *Islamic Science and Engineering*, notes that the *noria* was used in China in the first century BC, and he says that there is a possibility 'that it was invented somewhere in the highlands of southwest Asia, perhaps in northern Syria or Iran, and was diffused to the east and west from its area of origin'. Eventually both the *noria* and the *saqia* crossed the Atlantic to the New World.

Water-wheels were also used to power mills in antiquity in regions that subsequently became part of the Islamic world. There are three types of water-wheel, the undershot, overshot and horizontal, depending on whether the stream comes from above, below or beside the wheel. Vitruvius describes an undershot water-wheel in *De architectura*; the Banu Musa, writing in the ninth century, describe a vertical wheel that powered a fountain they designed; while al-Muradi, who worked in al-Andalus in the eleventh century, mentions an overshot wheel.

According to Al-Hassan and Hill, 'Tidal mills were in use in Basra in the eleventh century AD, whereas the earliest recorded record of their use in Europe was a hundred years later.' They go on to note that mills were more usually built on the banks of swiftly flowing rivers 'in every province of the Muslim world from Spain and North Africa to Transoxiana', mostly for the processing of cereals.

They also point out that 'Paper mills were introduced to Samarqand in 134 AH (751 AD) and were erected soon afterwards in many parts of Islam.'

Joseph Needham, in his multivolume work on *Science and Civilization in China*, notes that 'the history of windmills really begins with Islamic culture, and in Iran'. The Banu Musa mention windmills in their *Book on Mechanical Devices*, where they say that they 'are commonly used by the people'. These windmills were of the horizontal type and came into common use in Europe in the sixteenth century. According to Needham, 'this must surely have been a westward transmission from Iberian culture originally derived from Muslim Spain'. Needham believes that the vertical windmill was a European invention, stimulated by the horizontal type that had been acquired from al-Andalus.

The earliest work in Arabic on agriculture is the *Kitab al-azminah* (*The Book of the Times*), by the ninth-century Christian physician Yuhanna ibn Masawayh, the teacher of Hunayn ibn Ishaq, who also wrote on the subject. Another important text was the *Geoponica*, a multivolume collection of agricultural lore compiled for the Byzantine emperor Constantine VII Porphyrogenitus (r. 913–59), translated into both Persian and Arabic.

The clepsydra, or water-clock, was probably invented in Egypt in the mid-second millennium BC, and was widely used in the ancient Greek world. There are stories that Harun al-Rashid presented an elaborate water-clock to Charlemagne, and it is known that one was designed by Ibn al-Haytham. The earliest extant description in Arabic of a water-clock is by al-Muradi. Al-Zarqallu, also working in the eleventh century, built two large water-clocks in Toledo, one of which was still working in the second quarter of the twelfth century. Al-Khazini describes two steelyard clepsydras in *The Book of the Balance of Wisdom.* The most elaborate of all the ancient and medieval water-clocks are those of al-Jazari in *The Book of Ingenious Mechanical Devices.* Al-Hassan and Hill write of the technical advances made by al-Jazari and al-Muradi that would influence the development of mechanical clocks.

> Al-Jazari's clocks are full of ideas and techniques that are of importance in the history of machine design ... accurate calibration of small orifices; feed-back control methods; the use of paper models to establish intricate designs; the use of wooden templates; the static balancing of wheels; the use of laminated timber to minimise warping; one-way hinges; and tipping buckets. To these we should add the use of complex gears and the use of mercury in al-Muradi's clocks. The latter is of especial significance because a weight-driven clock with a mercury escapement appears in the *Libros del Saber*, a work written in Spanish at the court of Alfonso X of Castile about AD 1277 and consisting of translations and paraphrases of Arabic works.

The astronomer Taqi al-Din also wrote on mechanics and time-keeping. His book on *The Brightest Stars for the Construction of Mechanical Clocks*, written about 1565, was edited by Sevim Tekeli in 1965 with English and modern Turkish translations. Al-Hassan and Hill point out some of the technical innovations in this and other works by Taqi al-Din.

> ... he described the construction of a weight-driven clock with verge-and-foliot escapement, a striking chain of gears, an alarm, and a representation of the moon's phases. He also described the manufacture of a spring-driven clock with a fusee drive. He mentions several mechanisms invented by himself, including, for example, a new system for the striking train of a clock. He is known to have constructed an observatory clock and mentions elsewhere in his writings the use of the pocket watch in Turkey...

So far as medieval Islamic technology was concerned, there was no distinction between chemistry and alchemy, both of which were referred to by the Arabic word *al-kimiya.* Aside from the theory and mystical philosophy behind it, the practice of alchemy demanded a detailed knowledge of the physical properties of the materials involved, and the processes to which they were subjected represent the beginning of chemistry as we know it today. As we have seen, Islamic alchemy began during the reign of Harun al-Rashid with Jabir ibn Hayyan, the Latin Geber, whose recipe for making cinnabar, or mercuric oxide, would fit perfectly well in a modern chemistry handbook:

> To convert mercury into a red solid: take a round glass vessel and pour a convenient quantity of mercury into it. Then take a Syrian earthenware vessel and into it put a little powdered yellow sulfur and pack it round with more sulfur up to the brim. Place the apparatus in the furnace for a night, over a gentle fire ... after having closed the mouth of the earthenware pot. Now take it out, and you will find that the mercury has been converted into a hard red stone the colour of blood ... It is the substance which the men of science call cinnabar.

The philosopher and physician al-Razi, the Latin Rhazes, also wrote on alchemy, most notably in his *Kitab al-Asrar* (*Book of Secrets*). Here he is less interested in the esoteric philosophical background of alchemy than in the chemical substances, processes and laboratory equipment involved. Al-Razi divided chemical processes into twelve categories, the first two of which were distillation and sublimation, the vaporisation of a solid without passing through the liquid phase. His book describes the equipment, instruments and apparatus used in all of these processes, a list that would be added to in later works on Islamic alchemy. Al-Razi divided the equipment into categories, the first of which concerned smelting and other processes, while the second was for experimenting with chemical substances.

Among the substances that al-Razi describes in his *Kitab al-Asrar* is *naft*, or petroleum, which in modern times was to become the principal source of wealth of a number of Islamic countries in the Middle East. He also worked with oil lamps, or *naffata*, for which he used both vegetable oils and refined petroleum as fuel. He and other Muslim scientists distinguished between 'black *naft*', or crude oil, and the distillates, which they called 'white *naft*'. Al-Masudi, after visiting the oilfields of Baku around 915, reported that 'vessels carrying trade sail to Baka [Baku] which is the oilfield for white *naft* and other [kinds]; and there is not in the world – and God knows better – white *naft* except in this spot'. According to al-Hassan and Hill, in the thirteenth century 'wells were dug in Baku to get down to the source of the naft, and it was at this time that Marco Polo reported "a hundred shiploads might be taken from it at one time"'.

The philosopher al-Kindi wrote about distillation in his *Kitab Kimiya' al-'Itr wa al-Tas'idat* (*Book of Perfume Chemistry and Distillation*). Among the many kinds of apparatus that he describes and illustrates is the retort, a vessel in which substances are distilled or decomposed by heat. As al-Hassan and Hill note concerning the process of distillation in the side-tube of the retort: 'On present evidence it is usually suggested that the use of cooling water was a later development that occurred in the West... However it is significant that the cooling-bath that embraced the whole upper part of the still was always known as the "Moor's head",' which leads them to suggest that the still is an Arabic invention. As further evidence they cite al-Kindi, who says 'In the same way one can distill wine using a water-bath, and it comes out the same colour as rose-water.'

A study of Islamic alchemical literature reveals that Muslim scientists produced inorganic acids through the distillation of alum, sal amoniac, saltpetre, vitriol and common salt. Al-Razi describes how he made hydrochloric acid, known in Arabic as *ruh al-milh* (spirit of salt): 'Take equal parts of sweet salt, bitter salt, Tabarzad salt, salt of al-Qali and salt of urine. After adding an equal weight of good crystallised sal-amoniac, dissolve by moisture and distil [the mixture]. These will distil to give over a strong water which will cleave stone instantly.'

The *al-Qali* mentioned by al-Razi is the source of the chemical term alkali, a soluble salt obtained from the ashes of plants and consisting largely of potassium or sodium carbonate.

Al-Razi also gives recipes for making hard soap, which was used in the Muslim world long before it was manufactured in Europe. The basic recipe used *al-Qali* and olive-oil, sometimes with an addition of *natrun* (natron), or crude sodium carbonate. As Al-Hassan and Hill point out: 'Soap manufacture became an important industry in many Islamic lands, especially in Syria. Coloured perfumed toilet soap as well as some medicinal soaps were made and exported, and Syrian towns like Nablus, Damascus, Aleppo and Sarmin were famous for their products.'

Syria was renowned since antiquity for its glass industry, which flourished again with the rise of Islam, particularly in Damascus. Syria continued to dominate the market until it was supplanted by Venice in the late thirteenth century. According to al-Hassan and Hill: '... the secrets of Syrian glass-making were brought to Venice, everything necessary being imported directly from Syria – raw materials as well as the expertise of the Syrian-Arab craftsmen. Once it had learnt them, Venice guarded the secrets of the technology with great care, monopolising European glass manufacture until the techniques became known in seventeenth-century France.'

Metallurgy played an important part in the Islamic world, with gold, silver and copper used for minting coins; iron and steel for manufacturing arms, agricultural implements and tools; lead and zinc for alloying bronze and brass; lead for weights and other purposes. A number of Islamic scholars wrote on the technology of mining and metallurgy, most notably al-Biruni and al-Kindi. Al-Biruni writes of gold mines in the Maghrib, the processing of gold ores in the Sind, the alloying of copper and lead to make bronze, and the creation of steel from iron.

Damascus was famous for its patterned steel swords, of which Cyril Smith notes in his history of metallurgy that 'The geographical distribution of these swords seems to have been practically co-extensive with the Islamic faith and they continued to be made well into the nineteenth century.' His analysis of the patterns of these swords corroborates the description of their processing given by al-Biruni. Islamic and Indian metalworkers also devised a welding technique for making swords and gun barrels, one that Cyril Smith has called 'an interesting anticipation of modern powder metallurgy'. The product was called 'Damascus', though it was quite different from Damascus steel.

The sword and the bow were the main weapons of the first armies of Muhammad and then of his successors, the caliphs, which subsequently developed an extensive armoury of artillery, gunpowder, from China and siege machinery that predates Islam, along with fortifications and military communications. Muslim armies were also equipped with incendiary weapons and other methods of chemical warfare devised by alchemists, all of which are described in Islamic treatises on military technology and the arts of war.

These treatises, of which more than fifty survive, are usually classified under three headings. The first category is *furusiyya*, or treatises on horsemanship, tournament exercises, cavalry exercises, battle formations, military organisation, training and theory. The two most important of the extant *furusiyya* treatises are *The Book on Horsemanship for the Holy War*, by Najm al-Din Ayyub al-Ahdab al-Rammah (d. 1294) and *An End to Questioning and Desiring Further Knowledge Concerning Different Exercises of Horsemanship*, written about 1400 by Muhammad ibn 'Isa al-Aqsara'i.

The second category includes treatises on archery, the earliest of which is *Rules of Conduct for War and Bravery*, written in Persian by Fakhr-i Mudabbir, who dedicated it to Shams al-Din Iltumish, the Moghul Sultan of Delhi (r. 1211–36). The earliest of the Arabic works on archery is perhaps a treatise written by Taybugha al-Baklamishi (d. 1394).

The third category comprises treatises on fortifications and siege warfare, including battle formations, types of commanders and their attributes, camping and making palisades, spying and stratagems. The earliest of the two most important treatises of this type is *Instructions of the*

Masters of the Skills of the Methods of Salvation in Wars, by Murdab ibn 'Ali al Tarsusi, who wrote it for Saladin around 1187. The other is *Things Worth Mentioning About Warlike Stratagems*, written in 1205 by 'Ali ibn Abi Bakr al-Harawi (d. 1214).

The historian Ibn Khaldun, writing about 1377, describes the use of cannon during a siege in the Maghrib a century earlier by Sultan Abu Yusuf. He writes that the sultan 'installed siege engines ... and gunpowder engines which project small balls of iron. These balls are ejected from a chamber placed in front of a kindling fire of gunpowder; this happens by a strange property which attributes all actions to the power of the Creator.'

The Islamic empire was created both by land and by sea, and while its armies extended their conquests from India to al-Andalus their navies raided the shores and islands around the Mediterranean and along the coasts of Africa and Asia, with their merchant ships trading across the entire Muslim world, the *dar-al Islam*, and beyond to the limits of the known world.

The enormous expansion of Islam by sea gave rise to travelogues by Muslim mariners, journeys perpetuated in myth by the voyages of Sinbad the Sailor. It also gave rise to Arabic works in geography and cartography, based on Ptolemy's *Geography*, the earliest being al-Khwarizmi's *Surat al-ard* (*The Figure of the Earth*).

The last of the great Islamic cartographers was the Ottoman admiral Piri Reis (ca. 1465–1555), who in 1513 produced his first world map, which three years later he presented to Sultan Selim I. This was based on a score of older maps that he had collected, including charts that had been drawn for Christopher Columbus during his exploration of the New World. Then in 1521 he completed his *Kitab-ı Bahriye* (*Book of Navigation*). This was a compilation of his observations and geographical knowledge, including the discoveries of Columbus and Vasco da Gama, along with his own maps and drawings of the cities around the Mediterranean coasts as well as considerable information on navigation and nautical astronomy. Four years later he presented a revised edition of the book to Sultan Süleyman the Magnificent. He then compiled a map of the known world, which he presented to Süleyman in 1528. Only a fragment of that map survives, showing Greenland and North America from Labrador and Newfoundland south as far as Florida, Cuba and parts of Central America.

Architectural and industrial technology were an important part of Islamic civilisation from the very beginning. Mosques and madrasas continued to be adorned with beautiful ceramics on into the sixteenth century, when the superb Iznik tiles were used in virtually all of the buildings erected by the great Ottoman architect Sinan (ca. 1492–1588).

Textile manufacture early on became the leading industry in the Islamic world. The Arabs introduced the cotton textile industry to al-Andalus in the eighth century, and from there it spread to France in the twelfth century and then in turn to Flanders, Germany and then to England. Europe also imported cotton from Islamic countries, first from Syria and later from Egypt. Islamic silk textiles first made their way to the West in Spain and Italy, spreading from there through the rest of Europe.

The making of paper, which originated in China, spread to the West through the Muslim world. According to al-Hassan and Hill, 'Arabic sources report that their paper industry started at Samarkand in the mid-eighth century, when some Chinese prisoners of war were taken there' though there are those who believe that this is just a legend. They also note that 'factories for paper-making were established in Baghdad at the end of the eighth century', after which paper mills were built in Syria, Egypt, the Maghrib, al-Andalusia and Muslim Sicily. They go on to say that 'Only later did paper-making spread to Europe and then rather slowly, the first paper mill being established at Fabriano in Italy in 1276; it took another century and more before a mill was established at Nüremberg in Germany in 1390.'

Several Arabic technological manuscripts describe the techniques of paper-making, bookbinding and the production of writing materials. One such work is *The Handbook of Scribes and the Tool of the Wise*, written around 1025 by al-Mu'iz ibn Badis, who describes the techniques of making paper, books, inks and glue. Since many Islamic manuscripts were illustrated with drawings and miniature paintings, he also describes the making of pigments, paints, varnishes and lacquers, which were applied by pen or brush to paper, leather and other surfaces, including animal-skin.

The translation programme at the *Bayt al-Hikma* would not have been possible without the paper mills of Baghdad, which were also very likely the source of the profusion of manuscripts produced in the early 'Abbasid period (though the fact that there are almost no extant texts from this time means that the material on which they were written can only be guessed at). It is important to note however that this paper making technology was acquired from the Chinese. And thus a technological advance played a vital role in the very beginning of Arabic science, one of the myriad ways in which the technology developed in Muslim lands became part of the Islamic heritage.

CHAPTER 12

Al-Andalus

Before the Muslim conquest the Iberian peninsula was ruled by the Visigoths, a barbarian Germanic people who had conquered the region when the Roman Empire collapsed in the early fifth century AD. The Visigoths were divided into three tribes, the Suevi, the Alani and the Vandals. Some of the Vandals crossed over to conquer the Roman province of Africa, where they were still ruling when the Arabs conquered the Maghrib. When the Arabs learned that their predecessors had crossed over from the Iberian peninsula they referred to that region by a distorted version of the name 'Vandals', calling it al-Andalus.

The Muslim conquest of the Iberian peninsula began in the spring of 711, when Musa ibn Nusayr, the Arab governor of the Maghrib, sent an army across the strait under Tariq ibn Ziyad. The great peninsular rock on the European side of the strait was thenceforth called Jabal Tariq, which in English came to be known as Gibraltar. The last Visigoth king, Roderic, was defeated and killed in July 711 by Tariq, who went on to capture Cordoba and Toledo, the Visigoth capital.

Musa followed across the straits with an even larger army, and after taking Seville and other places he joined Tariq in Toledo. Musa was then recalled to Damascus by the Umayyad caliph, leaving the conquered lands in the hands of his son 'Abd al-Aziz, who in the three years of his governorship (712–15), extended his control over most of the Iberian peninsula, thenceforth known to the Arabs as al-Andalus.

When the first 'Abbasid caliph, Abu'l-'Abbas al-Saffah (r. 749–54), came to power in Damascus he sought to consolidate his power by slaughtering all of the members of the Umayyad family. One of the Umayyads, 'Abd al-

Rahman, escaped to the Maghrib and then to al-Andalus, where in 756 he established himself in Cordoba, taking the title *amir.* This was the beginning of the Umayyad dynasty in Spain, which was to rule al-Andalus until 1031. ‘Abd al-Rahman I (r. 756–88) established Cordoba as his capital, and in the years 784–86 he erected the Great Mosque, which was rebuilt and enlarged by several of his successors.

The Umayyad dynasty in al-Andalus reached its peak under ‘Abd al-Rahman III (r. 912–61), who in 929 took the title of caliph, emphasising the independence of al-Andalus from the ‘Abbasid caliphate in the East. This began the golden age of Muslim Cordoba, known to Arab chroniclers as ‘the bride of al-Andalus’. The golden age continued under ‘Abd al-Rahman’s son and successor al-Hakam II (r. 961–76), and his grandson Hisham II (976–1009), who was a puppet in the hands of his vizier al-Mansur.

‘Abd al-Rahman chose a site outside Cordoba to build the magnificent palace of Madinat al-Zahra, ‘the Radiant’. Al-Hakem built one of the greatest libraries in the Islamic world in Cordoba, rivalling those at Baghdad and Cairo. The caliph’s library, together with the many free schools he founded in his capital, gave Cordoba a reputation for learning that spread throughout Europe, attracting Christian scholars as well as Muslims, not to mention the Jews who lived under Islamic rule. As the Maghrib historian al-Maqqari was to write of tenth-century Cordoba: ‘in four things Cordoba surpasses the capitals of the world. Among them are the bridge over the river and the mosque. These are the first two; the third is Madinat al-Zahra; but the greatest of all things is knowledge – and that is the fourth.’

After al-Mansur’s death in 1002 the caliphate passed in turn to several claimants in the principal cities of al-Andalus, and finally it was abolished altogether in 1031. The fall of the caliphate was followed by a period of sixty years in which al-Andalus was fragmented into a mosaic of petty Muslim states, allowing the Christian kingdoms of northern Spain to start expanding south, beginning what came to be known then as the *reconquista.* The first major Christian triumph came in 1085, when Toledo fell to the king of Castile and Leon, Alfonso VI (r. 1072–1109).

The fall of Toledo led the petty Muslim rulers to seek help from the powerful ruler of the Almoravids in Morocco, Yusuf ibn Tashfin (r. 1061–1106). Yusuf crossed into al-Andalus in 1086, when he decidedly defeated Alfonso’s army, saving southern Spain from falling into Christian hands. This led to the domination of al-Andalus by the Almoravids, which lasted until the mid-twelfth century, when they were supplanted by another powerful dynasty from the Maghrib, the Almohads. During the reign of

'Abd al-Mu'min (r. 1130–63) the Almohads extended their power throughout both the Maghrib and al-Andalus. The Almohads suffered a crushing defeat in 1212 at the hands of a Christian coalition, which in the next half century seized the major Muslim cities in al-Andalus, taking Cordoba in 1236. Virtually all that remained of al-Andalus was the Banu Nasr kingdom of Granada, which hung on until its capture in 1492 by Ferdinand II of Aragon and Isabella of Castile, the 'Catholic Kings', who drove most of the Moors from Spain, along with the Jews. A few remained, however, protected by their Christian lords, retained for their skills or converted under the Inquisition until 1609, when there was another great wave of expulsion.

'Abd al-Rahman II (r. 822–52) contributed to the development of science in al-Andalus by sending an agent to the East to buy manuscripts, which an anonymous Maghribi chronicler says included astronomical tables as well as works in astronomy, philosophy, medicine and music. The *emir* was keenly interested in astronomy and astrology, perhaps stimulated by a total eclipse of the sun on 17 September 833, which so terrified the people of Cordoba that they quickly gathered at the Great Mosque to pray for divine deliverance.

The *emir*'s court poet and astrologer was 'Abbas ibn Firnas (d. 887), born in Roda of Berber origin, who was also an astronomer, physician, inventor and musician. Ibn Firnas introduced a version of al-Khwarizmi's astronomical tables, the *Zij al-Sindhind*, which would subsequently be of considerable influence on the development of astronomy in Christian Europe. With the *emir*'s patronage, Ibn Firnas built an observatory in Cordoba, with a planetarium, an armillary sphere and a water-clock capable of indicating the times of prayer. He invented a metronome, discovered how to cut quartz, and made a celestial sphere that he could adjust to appear cloudy or clear according to the weather. He also attempted to fly by leaping from the top of the Rusafa palace in Cordoba with a hang-glider of his own invention, made of feathers attached to a wooden frame. He apparently managed to glide for some distance but suffered injuries in a rough landing, which his critics attributed to his failure to observe the manner in which birds use their tail feathers when they alight on a branch.

Tenth-century Cordoba was renowned for its school of physicians, presided over by the Jewish doctor Hasday ibn Shaprut (ca. 915–ca. 990), vizier of 'Abd al-Rahman III and later personal physician of Hisham II. Hasday also supervised the imperial translation activities and carried out diplomatic missions on behalf of the caliphate. One of his diplomatic activities involved the reception of an ambassador from the Byzantine capital Constantinople in 949. The envoy brought with him presents for ‘Abd al-Rahman III from the emperor Constantine VII Porphyrogenitus (r. 913–59), one of them being a superb Greek manuscript of *De Materia Medica* of Dioscorides.

No one in Cordoba knew enough Greek to read the manuscript, so the ambassador arranged for a Byzantine monk named Nicholas to be sent to Cordoba, where he arrived in 951, along with a Greek-speaking Arab from Sicily. Nicholas and the Arab then explained Dioscorides’ work to a group of Cordoban scholars headed by Hasday, thus contributing to the studies of pharmacology in al-Andalus. *De Materia Medica* subsequently was translated from Arabic into Latin for the education of pharmacists and physicians in Christian Europe.

Hasday then entered into correspondence with the Empress Helena, wife of Constantine Porphyrogenitus, asking her to protect the Jews of Constantinople from persecution. He also corresponded with Khan Joseph, ruler of the Khazars, a Turkic tribe in the Crimea, who had in the late eighth or early ninth century converted to Judaism.

The Jewish physician and philosopher Isaac ben Solomon Israeli (ca. 855–ca. 955) was an older contemporary of Hasday. He was born in Egypt and sometime after 900 he moved to Ifriqiya (‘Africa’, now Tunisia). There he became personal physician to the last emir of the Aghlabids, the dynasty named for Ibrahim ibn al-Aghlab, who had been made hereditary governor of Ifriqiya in 800 by Harun al-Rashid. When the last Aghlabid emir was deposed Israeli became court physician to Ubayd Allah al-Mahdi (r. 909–34), founder of the Fatimid dynasty in Ifriqiya.

Israeli wrote several medical treatises in Arabic that were popular in the Islamic world, and, after their translation into Latin, were much used in Catholic Europe as well. The treatises were also translated into Hebrew. The best known of his medical works are the *Book of Fevers*, the *Book of Foodstuffs and Drugs*, and the *Book of Urine*.

His major works are the *Book of Definitions*, the *Book of Substances*, the *Book on Spirit and Soul*, the *Chapter on the Elements* and the *Book on the Elements*. The writings had considerable influence on Christian thinkers, including Albertus Magnus, Thomas Aquinas, Roger Bacon and Nicholas of Cusa, as well as on the great Jewish poet and philosopher Solomon ben Gabirol.

The principal source of information about the Cordoban medical school is Sulayman ibn Hasan ibn Juljul al-Andalusi (944–ca. 994). Ibn Juljul studied medicine in Cordoba between the ages of fourteen and twenty-four with a group headed by Hasday ibn Shaprut and the Byzantine monk Nicholas. Later he became the personal physician of Caliph Abd-al Rahman III. His most important work, entitled *Generations of Physicians* *and Wise Men*, is one of the most complete extant source in Arabic on the history of medicine. It is of particular interest because he uses not only Arabic translations of Greek sources and Islamic sources but also the works of western Christian physicians who had treated the early Andalusian emirs, their works having been translated from Latin to Arabic at Cordoba in the eighth and ninth centuries. He says that most of the physicians practising in al-Andalus up to the time of 'Abd al-Rahman III were Mozarabs, or Christians living under Muslim rule who had taken Arabic on as their language and whose culture was connected with that of al-Andalus, and that the principal source of their knowledge was 'one of the books of the Christians that had been translated'.

Ibn Juljul also wrote a treatise on *De Materia Medica* of Dioscorides, probably based on the manuscript that had been sent from Constantinople. He wrote another book on the plants and remedies that had not been described by Dioscorides. The works of Ibn Juljul remained popular in al-Andalus for some time, and one of them may have been translated into Latin, since Albertus Magnus quotes from a treatise called *De Secretis* which he attributes to a certain Gilgil, probably a corruption of 'Juljul'.

The physician and pharmacologist Abu'l Qasim al-Zahrawi (ca. 936–ca. 1013), the Latin Abulcasis, was a contemporary of Ibn Juljul. His last name comes from his birthplace, the imperial Cordoban suburb of Madinat al-Zahra, where he spent most of his life. His only known work is the *Kitab al-Tasrif*, a medical encyclopedia in thirty volumes, which he completed in about the year 1000, encompassing the experience of nearly half a century as a physician. The encyclopedia covers every aspect of medicine, including the design and manufacture of surgical tools, midwifery, pharmaceutical preparations, diet, hygiene, medical terminology, weights and measures, medical chemistry, human anatomy and physiology, therapeutics and psychotherapy. Al-Zahrawi recommended that physicians should specialise in a particular branch of medicine, because 'Too much branching and specialising in many fields before perfecting one of them causes frustration and mental fatigue.' He particularly emphasised the importance of bedside medicine and the bond between doctor and patient, writing that 'Only by repeated visits to the patient's bedside can the physician follow the progress of his medical treatment'.

Al-Zahrawi was a great educator and encouraged young people to study medicine after completing their studies in the humanities, philosophy, astronomy and mathematics. He was also a natural philosopher and described medicinal plants and the preparation of pharmaceuticals from chemical substances. He was a pioneer in the use of drugs in psychotherapy, and he made an opium-based medicine that he called ‘the bringer of joy and gladness, because it relaxes the soul, dispels bad thoughts and worries, moderates temperaments, and is useful against melancholia’. His work was translated into Latin by Gerard of Cremona and others and became very popular in western Europe.

A new phase in the development of astronomy in al-Andalus begins with the work of Abu Maslama al-Majriti, who was born in Madrid in the second half of the tenth century and studied in Cordoba, where he died in 1007. He seems to have studied with the group of scholars patronised by ‘Abd al-Rahman III and may have served as the caliph’s astrologer.

Al-Majriti and his student Ibn al-Saffar (d. 1034) improved the astronomical tables of al-Khwarizmi and adapted them for the latitude of Cordoba, a work that passed to Christian Europe through a Latin translation by Adelard of Bath. Two other extant works of al-Majriti are the *Commercial Arithmetic* and a brief *Treatise on the Astrolabe*, while his Arabic edition of Ptolemy’s *Planisphaerium* survives in a Latin version by Herman of Dalmatia. The eleventh-century historian Ibn Sa’id of Toledo says that al-Majriti ‘applied himself to the observation of the heavenly bodies and to understanding the book of Ptolemy called the *Almagest*’, and that he was ‘the author of a summary of the part of al-Battani’s table concerning the equation of the planets’. According to the fourteenth-century astronomer Ibn al-Shatir, al-Majriti was one of a number of Islamic astronomers who produced theories of the motion of the celestial bodies that were different from the standard Ptolemaic model.

Al-Majriti was once thought to be the author of the *Ghayat al-hakim* (*The Aim of the Wise*), as alleged by Ibn Khaldun, but this attribution has now been rejected. This work was translated into Castilian in 1256 through the patronage of King Alfonso X of Castile. It was later translated into Latin under the title of *Picatrix*, a corruption of Buqratis, the Arab name of Hippocrates, on the supposition that he, and not al-Majriti, was the author, who is described on the title page as being a ‘very wise... philosopher... most skilled in mathematics ... [and] very learned in the arts of necromancy’.

The *Picatrix* has been described as ‘a compendium of magic, cosmology, astrological practice, and esoteric wisdom in general’, which ‘provides the most complete picture of superstitions current in eleventh-century Islam’. Lynn Thorndike devotes a whole chapter of his *History of Magic and Experimental Science* to the *Picatrix*, which he describes as a ‘confused compilation of extracts from occult writings and a hodgepodge of innumerable magical and astrological recipes’.

The occult knowledge in the *Picatrix* may have come to al-Andalus from the eastern Islamic world. Ibn Juljul mentions a physician named al-Harrani, (from Harran) who practised in Cordoba at the court of ‘Abd al-Rahman II, and he also writes of two other physicians of that name who may be grandsons of al-Harrani. These are Ahmad and ‘Umar ibn Yunus al-Harrani, who before coming to Cordoba had studied at Baghdad with Thabit ibn Sinan ibn Thabit ibn Qurra, who as his name indicates was a grandson of the great Thabit ibn Qurra of Harran.

Al-Majriti is also credited with an Arabic lapidary, or work on gems and their medical and magical properties. The lapidary was used by William of Auvergne (d. 1249), who refers to it in writing that the tortoise stone can produce visions and revelations. This wizard stone is described thus in the lapidary. He writes that ‘The virtue of the stone is that when it is placed under the tongue, which has first been anointed with honey, the tongue utters knowledge of the future, as long as the stone remains under it.’

The beginning of Arabic philosophy in al-Andalus comes with the work of Ibn Hazm (994–1064), who was born and spent most of his life in Cordoba, where his father and grandfather had been functionaries in the Umayyad court. His best-known philosophical work is his *Book on the Classification of the Sciences.* Aside from his many philosophical works, he also wrote poetry and treatises on history, jurisprudence, ethics and theology. His most famous poetical work is entitled *Tawq al-hamama*, or *The Dove’s Neck-Ring*, a treatise on the art of love, which he says is ‘a serious illness’.

> Love, may God honor you, is a serious illness, one
> whose treatment must be in proportion to the
> affliction. It’s a delicious disease, a welcome malady.
> Those who are free of it want not to be immune, and
> Those who are stricken by it want not to be cured.

Ibn Hazm was particularly qualified to write a book on the art of love, he writes, having been brought up to the age of fourteen in the harem, or women’s quarters, of his family home: ‘I have observed women at first hand and I am acquainted with their secrets to an extent that no one else could claim, for I was raised in their chambers and I grew up among them and knew no one but them.’ He goes on to say that ‘women taught me the Qu’ran, they recited to me much poetry, they trained me in calligraphy’.

The Islamic schools of the time in Cordoba employed several women copyists, as did the city’s book market, whereas more highly educated women worked as teachers and librarians, while a few even practised medicine and law.

Ibn Hazm believed in revelation, but he felt that ‘the first sources of all human knowledge are the soundly used senses and the intuition of reason, combined with the correct understanding of a language'. He said that the first Muslims had experienced divine revelation directly, whereas those of his own time were exposed to contrary beliefs and needed logic to preserve the pure teachings of Islam, so that they can know 'the reality of things and ... discern falsehood without a shred of doubt'.

Ibn Hazm also wrote a work on ethics entitled *The Characters and Conduct Concerning the Medicine of Souls*. There he describes the Socratic ideal of moderation in all things that governed his own way of life: 'In this book I have gathered together many ideas which the Author of the light of reason inspired in me as the days of my life passed and the vicissitudes of my existence succeeded one another. God granted me the favour of being a man who has always been concerned with the vagaries of fortune.'

The leading Andalusian astronomer in the century after al-Majriti was Ibn Mu'adh al-Jayyani (d. 1093), whose last name comes from the fact that he was a native of Jaen, east of Cordoba. His best known work is the *Tabulae Jahen*, a set of astronomical tables based on al-Khwarizmi's *Sindhind* and adapted for the latitude of Jaen. His tables were an improvement over the *Sindhind*, for he took into account the precession of the equinoxes, which al-Khwarizmi had ignored, and he utilised advances in astronomical theory made by al-Biruni and his other predecessors. *The Tabulae Jahen* also gives detailed instructions in such practical matters as determining the times of prayer, the direction of Mecca, the visibility of the new moon to establish the beginning of the Islamic months, the prediction of lunar eclipses, and the casting of horoscopes, all of which made it very useful for later mosque astronomers.

Al-Jayyani's other writings include treatises on astronomy and mathematics. His astronomical works include a treatise dealing with the phenomena of twilight and false dawn, which in its Latin translation was popular from the medieval era up to the Renaissance. His treatise *On the Total Solar Eclipse* describes an eclipse of the sun visible at Jaen on 1 July 1079. One of his mathematical works is a treatise on spherical trigonometry. Another is his treatise *On Ratio*, which he says he composed 'to explain what may not be clear in the fifth book of Euclid's writing to such as are not satisfied with it'. Unlike many other Islamic mathematicians, he did not try to prove Euclid's definition of parallel lines, writing that 'There is no method to make clear what is clear in itself'.'

Al-Jayyani's contemporary Abu 'Ubayd 'Abdallah ibn 'Abd al-'Aziz ibn Muhammad al-Bakri (ca. 1010–94) was one of the pioneers of Andalusian geography. Al-Bakri was born in Huelva, but spent most of his life in Cordoba, Almeria and Seville. His most important work is the *Book of Roads and Kingdoms*, completed in 1068, a description of land and sea routes for the use of travellers. The book describes Europe, North Africa and Arabia, giving useful facts on the main cities, geography, climate, history, people and social conditions. His sources include Jewish and Islamic travellers and writers.

Al-Jayyani's treatise on spherical trigonometry was indirectly transmitted to parts of Christian Europe through a work of Jabir ibn Aflah, known in Latin as Geber, an astronomer and mathematician who flourished in Seville in the first half of the twelfth century. One of Jabir's most important works, in which he used and added to al-Jayyani's methods in spherical trigonometry, is an adaptation of Ptolemy's astronomical theories in a treatise entitled *Islah al-Majisti* (*Correction of the Almagest*). According to Ibn al-Qifti, the *Islah al-Majisti* was revised ca. 1185 by Moses Maimonides and his student Joseph ben Yehuda ben 'Aqnin, and it was translated from Arabic to Hebrew by Moses ben Tibbon in 1274. The unrevised text was translated into Latin by Gerard of Cremona in the second half of the twelfth century and was used by European astronomers and mathematicians up until the seventeenth century. European mathematicians were particularly influenced by Jabir's version of spherical trigonometry, which was used by Regiomontanus in his *De triangulis*, published in the early 1460s, a work 'which systematized trigonometry for the Latin West', according to R. P. Lorch. Lorch also notes that Copernicus made use of the work of Jabir, whom he called an 'egregious calumniator of Ptolemy'.

Another set of astronomical tables was compiled for Toledo around 1069. These were the famous *Toledan Tables*, known only through a Latin translation, which survives in an enormous number of manuscript copies. The tables, which were an adaptation of earlier works from Ptolemy through al-Khwarizmi and al-Battani, were prepared by a group of astronomers, the best known of whom was Abu'l-Qasim Sa'id (d. 1070), the *qadi*, or judge, of Toledo.

Another notable member of the group was al-Zarqallu (d. 1100) (arguably more famous than Abu'l-Qasim), the Latin Arczachel, a self-educated artisan who worked for Abu'l-Qasim Sa'id as a maker of astronomical instruments and water-clocks. After Abu'l-Qasim Sa'id died, al-Zarqallu became director of the group that completed the new astronomical tables.

The observations that led to the *Toledan Tables* were continued for another three decades by al-Zarqallu, who left Toledo ca. 1078 because of the repeated attacks by the Christian king Alfonso VI and moved to Cordoba, where he lived for the rest of his days. The water-clocks built in Toledo by al-Zarqallu remained in use until 1133, when King Alfonso VII of Castile and Leon had them taken apart to see how they worked but could not reassemble them. Water-clocks of the type built by al-Zarqallu, which showed the motion of the celestial bodies, became popular in seventeenth-century Europe.

The *Toledan Tables* were used in both al-Andalus and in Christian Europe, where they were translated into Latin ca. 1140 as the *Marseilles Tables.* There are at least two tables under this name, one ascribed to Raymond de Marseilles, the other William of England, and though they used the Toledan Tables, they also referred to other material and thus their versions are not considered true translations. The original translators of the Tables are generally assumed to be John of Seville and Gerard of Cremone and the Tables were known before 1140 in southern France, where Raymond de Marseilles compiled his *Liber cursurum planetarum.* They remained in use until the fourteenth century, and a Latin version of the *Toledan Tables* was translated into Greek around 1340 in Cyprus, completing a remarkable cultural cycle. The tables are mentioned by Chaucer in 'The Franklin's Tale', where one of the characters is a magician-astrologer of Orleans, equipped with all the tools of his celestial trade:

> His tables Toletanes forth he brought
> Ful wel corrected, ne ther lacked noght,
> Neither his collect ne his expans yeres,
> Ne his rotes ne his othere geres…

After the fall of Cordoba to the Christians in 1252, western Arabic science continued in Granada, the last Muslim kingdom in al-Andalus, and in the Maghrib, though on a much diminished scale.

The mathematician Ibn al-Banna al-Marrakushi (1256–1321) was a native of Granada, though, as his last name indicates, he had some connection to Marrakech. He is known to have studied in both Marrakech and Fez, where he taught mathematics and astronomy at the Madrasa al-Attarin. Eighty-two of his works are known, of which the most famous is the *Summary of Arithmetical Operations*, a compendium of the lost works of the mathematician al-Hassar (fl. ca. 1200).

The mathematician al-Qalasadi was a native of Basta (now Baza) in Spain, but when the city was taken in 1486 by Queen Isabella of Castile he was forced to flee to the Maghrib, where he died at Beja in Tunisia. One of al-Qalasadi's works is a commentary on Ibn al-Banna's *Summary of Mathematical Operations.* The first of his own writings was the *Classification of the Science of Arithmetic*, which he followed with a simplified version entitled *Unveiling the Science of Arithmetic*, and then an abridgement of the latter work called *Unfolding the Secrets of the Use of Dust Letters* (i.e., Hindu numerals). The last two works were used in Moroccan schools for generations after the death of al-Qalasadi.

Al-Qalasadi died only about fourteen years after the fall of Granada in 1492, which ended the history of al-Andalus. The principal remnant of the intellectual world of Muslim Granada is the al-madrasa al-yusufiyya, founded in 1349 by the *emir* Yusuf I (r. 1334–54). Only fragments of the Moorish building remain, but it is still referred to by its original Spanish name, La Madraza, from madrasa, a Muslim school of higher studies, the last one in al-Andalus. La Madraza eventually became part of the University of Granada, which was founded in 1531 by the Emperor Charles V.

CHAPTER 13

From the Maghrib to the Two Sicilies: Arabic into Latin

The great scientists and philosophers of the Islamic West were as much at home in the Maghrib, as they were in al-Andalus. Some of them travelled widely in both the Muslim and Christian worlds, which from the late eleventh century onwards were beginning to share ideas in philosophy and science, particularly in Spain, North Africa, Sicily and southern Italy.

The first of the important translators of Graeco-Islamic science from Arabic into Latin is Constantine the African (fl. 1065–85). An account of his early life is given by a twelfth-century Salerno physician known only as Magister Mattheus F.

According to this account, Constantine was a Muslim merchant from North Africa who visited the Lombard court at Salerno in southern Italy, where he learned that there was no medical literature available in Latin. According to the Salerno physician's account, he went back to North Africa and studied medicine for three years, after which he returned to Salerno with a collection of medical writings in Arabic, perhaps as early as 1065.

The story goes that a few years later he converted to Christianity and became a monk in the Benedictine Abbey at Monte Cassino. There, under the patronage of the famous abbot Desiderius, later Pope Victor III, he spent the rest of his days in making Latin translations or compilations from Arabic medical texts.

Petrus Diaconus, historian of the monastery at Monte Cassino, lists a score of translations by Constantine, including works of Hippocrates and Galen as well as those of the Jewish physician Isaac Israeli and the Arabic writers Ibn al-Jazar and ʻAli ʻAbbas. His most ambitious work was the *Kitab al-Maliki* of ʻAli ʻAbbas, which he translated as the *Pantegne*, divided into two ten-chapter sections, *theorica* and *practica*, suppressing the name of the author and thus leaving himself open to charges of plagiarism. Constantine appears to have translated only about half of this work, which seems to have been completed by his student Johannes Afflacius.

There is no direct evidence to connect Constantine with the Medical School of Salerno, founded in the mid-eleventh century. Johannes Afflacius seems to have taught there and introduced Constantine's translations into the curriculum under the title of *Ars medicine* or *Articella*, which formed the foundation of a large part of European medical education on into the sixteenth century. Constantine had always emphasised that medicine should be taught as a basic part of natural philosophy, and the *theorica* section of the *Pantegne* provided the basis for this integrated study.

The systematic study of Aristotelian philosophy in al-Andalus began with Abu Bakr Muhammad ibn Yahya ibn al-Sa'igh ibn Bajja, known in Latin as Avempace. Ibn Bajja was born in Saragossa ca. 1070, and in the years 1110–18 he served as vizier to the Almoravid governor of the city, Ibn Tifilwit. After the Christian conquest of Saragossa he spent the rest of his life in Almoravid territory, moving in turn to Almeria, Granada and Seville. While in Seville he was imprisoned before being released due to the intervention of Ibn Rushd al-Jadd, grandfather of the philosopher Ibn Rushd (Ibn Rushd al-Jadd literally means 'grandfather of Ibn Rushd'). After his release he moved first to Jaen and then to Fez in Morocco, where he died in 1128. Tradition says that he died after eating an eggplant poisoned by his rivals, intellectuals in the Almoravid court in Fez. According to Ibn Tufayl, Ibn Bajja 'was so preoccupied with material success that death carried him off before his intellectual storehouses could be cleared and all his hidden wisdom known'.

Thirty-seven of Ibn Bajja's numerous works survive, many of them commentaries on the works of Aristotle, Galen and al-Farabi, along with three of his own works. His ideas influenced the thought of Ibn Tufayl (Abubacer), Ibn Rushd (Averroës) and Maimonides. There were few Latin translations of his works, nevertheless they influenced St Thomas Aquinas, who incorporated some of Ibn Bajja's ideas into his theology.

Ibn Bajja seems to have been the first Arabic philosopher in al-Andalus to oppose the Ptolemaic planetary model. He rejected the use of epicycles as being incompatible with Aristotle's doctrine of celestial motion, in which the planets move in perfect circles about the earth as a centre. But, according to Maimonides, he did use eccentric circles, i.e., circular orbits whose centres did not coincide with that of the earth.

Ibn Bajja's ideas on dynamics appear in his notes on Aristotle's *Physics.* Here he attempted to replace Aristotle's causal approach to dynamics with the notion of force as the cause of motion. He rejected the Aristotelian law of motion, which held that the velocity of a body is directly proportional to the motive power and inversely proportional to the resistance of the medium through which it moves. Instead, following John Philoponus, he said that motion would occur only when the motive power was greater than the resistance, and that the velocity was proportional to the difference between the power and the resistance. He argued further that even in a void a body had to traverse a definite distance in any given time, so that its velocity would be finite no matter how fast it was moving. This was counter to the Aristotelian notion that in a vacuum a body's velocity would be infinite, which was impossible, so that a void could not possibly exist.

Ibn Bajja was also an accomplished musician and poet. According to the thirteenth-century Tunisian writer al-Tifashi, Ibn Bajja 'combined the songs of the Christians with those of the East, thereby inventing a style found only in Andalus, toward which the temperament of its people inclined so that they rejected all others'.

Another contemporary of Ibn Bajja was the Jewish polymath Abraham ben Meir ben Ezra (1092–1167), known in Latin as Abenezra. Ben Ezra was born in 1092, either in Toledo or Tudela, and he lived in Cordoba before leaving Spain before 1140 to escape the persecution of Jews by the Almohads. He then travelled to the Maghrib, Egypt, Palestine, Italy, France and England, visiting London and Oxford in 1158, before returning to Spain, where he most likely died around 1167. His writings include poetry and works in Hebrew grammar and religious philosophy, as well as treatises in mathematics, astronomy, astrology and chronology. Ibn Ezra's own writings include biblical commentaries that were much admired by Spinoza. His astrological works, were very popular in medieval Europe and were translated into French, Catalan and Latin, and later into other languages.

One of ben Ezra's astronomical works is a Hebrew translation of a commentary on the *Sindhind*, the astronomical tables of al-Khwarizmi, by the tenth-century Andalusian mathematician and astronomer Ibn al-Muthanna.

Ben Ezra's only extant mathematical work is his S*efer ha-Mispar, The Book of Number*, written probably before 1160. This is of particular importance because it describes the so-called Hindu decimal positional number-system, which he represented using the first nine letters of the Hebrew alphabet with a circle for zero. He says in *The Book of Number* that this system originated with the 'Wise men of India', while in his translation of al-Muthanna's commentary on the *Sindhind* he remarks that al-Khwarizmi was the first Arabic scholar to understand the Hindu numbers.

Adelard of Bath (fl. 1116–42) was one of the leading figures among those who were involved in the organic acquisition of Arabic science – patrons, translators, travelers and scholars. In the introduction to his *Questiones Naturalis*, addressed to his nephew, Adelard writes of his 'long period of study abroad', first in France, where he studied at Tours and taught at Laon. He then went on to Salerno, Sicily, Asia Minor, Syria probably, Palestine and Spain. It was probably in Spain that Adelard learned Arabic – though we do not know this for certain – for his translation of the *Astronomical Tables* of al-Khwarizmi was from the revised version of the Andalusian astronomer Abu Maslama al-Majriti. The *Tables*, comprising 37 introductory chapters and 116 listings of celestial data, provided Christian Europe with its first knowledge of Graeco-Arabic-Indian astronomy and mathematics, including the first tables of the trigonometric sine function to appear in Latin.

Adelard was also the first to give a full translation of the *Elements* of Euclid into Latin, beginning the process that led to Euclid's domination of medieval European mathematics. He did three versions of the *Elements*, the first being from the Arabic of Al-Hajjaj, who probably had translated it from Greek for Caliph Harun al-Rashid.

Adelard says that his *Questiones Naturalis* was written to explain 'something new from my Arab studies'. The *Questiones* are seventy-six in number, 1–6 dealing with plants, 7–14 with birds, 15–16 with mankind in general, 17–32 with psychology, 33–47 with the human body, and 48–76 with meteorology and astronomy. Throughout he looks for natural rather than supernatural causes of phenomena, a practice that would be followed by later European writers.

One particularly interesting passage in this work comes when Adelard's nephew asks him if it were not 'better to attribute all the operations of the universe to God'. Adelard replies: 'I do not detract from God. Everything that is, is from him and because of him. But [nature] is not confused and without system and so far as human knowledge has progressed it should be given a hearing. Only when it fails utterly should there be a recourse to God.'

The *Questiones Naturalis* remained popular throughout the rest of the Middle Ages, with three editions appearing before 1500, as well as a Hebrew version. Adelard also wrote works ranging from trigonometry to astrology and from Platonic philosophy to falconry. His last work was a treatise on the astrolabe, in which once more he explained 'the opinions of the Arabs', this time concerning astronomy. The treatise describes the workings of the astrolabe and its various applications in celestial measurements, using Arabic terms freely and quoting from Adelard's other works, particularly his translations of Euclid's *Elements* and the planetary tables of al-Khwarizmi.

Little is known about John of Seville, who in the years 1135–53 translated a score of Arabic works, most of them astrological, but also including an astronomical manual by al-Farghani and a treatise on arithmetic by al-Khwarizmi in which he describes the Hindu number system. The best known work by John of Seville is his partial translation of the medical section of the pseudo-Aristotelian *Secretum secretorum* (*The Secret of Secrets*). A more complete translation was subsequently made by Philip of Tripoli, who in his preface describes how he was in Antioch when he discovered 'this pearl of philosophy... this book which contains something useful about almost every science'.

Toledo became a centre for translation from the Arabic after Alfonso VI, king of Castile and Leon, carried out the first major triumph of the *reconquista*, the Christian reconquest of al-Andalus, and captured the city in 1085.

Gundissalinus, archbishop of Segovia, did several translations and adaptations of Arabic philosophy, including works by al-Kindi, Ibn Rushd, al-Farabi, al-Ghazali and Ibn Sina, as well as one by the Jewish physician Isaac Israeli. The translations attributed to Gundissalinus were probably done by him in collaboration with others who were fluent in Arabic, though only in one work, the *De anima* of Ibn Sina, is his name linked with that of a co-author. There his collaborator was a Jew named Abraham ibn David, the Latin Avendaut, w ho is usually identified with the translator known as John of Seville.

Gundissalinus also wrote five philosophical works on his own, based largely on the books that he had translated as well as on Latin sources. He is credited with introducing Arabic-Judaic Neoplatonism to the Latin West and blending it with that of St Augustine and Boethius. His *De divisione philosophiae*, which incorporates the systems of both Aristotle and al-Farabi as well as others, is a classification of the sciences transcending the traditional division of studies in the *trivium* (grammar, rhetoric and logic) and *quadrivium* (arithmetic, geometry, astronomy and musical theory), and it influenced later schemes of classification.

Plato of Tivoli is known only through his work, at least part of which he wrote in Barcelona between 1132 and 1146. His name appears only as an editor of translations from the Arabic and Hebrew in collaboration with the Jewish mathematician and astronomer Abraham bar Hiyya ha-Nasi, also known as Abraham Judaeus, or, in Latin, Savasorda, a corruption of the Arabic Sahib al-shurta.

Savasorda's most important work is his Hebrew treatise on practical geometry, which he and Plato of Tivoli translated into Latin in 1145 as the *Liber Embadorum.* This was one of the earliest works on Arabic elementary, geometry and arithmetic to be published in Latin Europe, and it contains the first solution of the standard quadratic equation to appear in the West. It was also the earliest to deal with Euclid's *On Divisions of Figures*, which has not survived in Greek and only partially in Arabic. This work influenced Leonardo Fibonacci, who in his *Practica geometriae*, written in 1220, devoted an entire section to division of geometrical figures.

Savasorda also collaborated with Plato of Tivoli in translating the *Spherica* by Theodosius of Bithynia, and the two may also have worked together on books by Ptolemy and al-Battani, as well as on Abu Maslama al-Majriti's treatise on the astrolabe. The translations from the Arabic of seven other works are attributed to Plato, with or without Savasorda, five of them astrological, one on divination, and one medical, now lost. One of these works is Ptolemy's great treatise on astrology, the *Tetrabiblos*, which Plato of Tivoli translated into Latin as the *Tetrapartitium.* This was the first Latin translation of Ptolemy, appearing before the *Almagest* and the *Geography*, evidence of the great popularity of astrology in medieval Europe. It has also been suggested that Plato is the author of the Latin translation from the Arabic of Archimedes' *De mensura circuli.* Plato's translations were used by both Fibonacci and Albertus Magnus, and printed editions of some of them were published in the late fifteenth and early sixteenth centuries.

Translations were also sponsored by Bishop Michael of Tarazona during the years 1119–51, as evidenced by a dedication to him by Hugo Sanctallensis. This appears in Hugo's translation from the Arabic of an abridged version of Ptolemy's *Tetrabiblos*, entitled *Centiloquium.* Hugo's preface says that the *Centiloquium* was commissioned by Michael to serve as a guide to the many astrological works that had been made available to the bishop. Hugo's other translations, all from Arabic sources, are on astrology and various forms of divination, including aeromancy, hydromancy and pyromancy, prognostication by observing patterns in air, water and fire, respectively, as well as two short treatises on spatulamancy, foretelling the future by examining the shoulder blades of slaughtered animals.

Gerard of Cremona (1114–87) was the most prolific of all the Latin translators, by far. The few details that are known of Gerard's life come mostly from a short biography and eulogy written by his companions in Toledo after his death, together with a list of seventy-one works that he had translated. This document was found inserted at the end of Gerard's last translation, that of Galen's *Tegni* with the commentary of 'Ali ibn

Ridwan. It notes that Gerard completed his education in the schools of the Latins before going to Toledo, which he would have reached by 1144 at the latest, when he would have been thirty years old. The *vita* goes on to say that it was his love of Ptolemy's *Almagest*, which he knew was not available in Latin, that drew Gerard to Toledo, and 'there, seeing the abundance of books in Arabic on every subject ... he learned the Arabic language, in order to be able to translate'.

Gerard also lectured on Arabic science, as evidenced by the testimony of the English scholar Daniel of Morley, who had first gone to Paris, but had left there in disappointment, going to Toledo to hear the 'wiser philosophers of the world', as he remarks in his *Philosophia*. Daniel gives a detailed account of meeting 'Gerard of Toledo' and listening to his public lectures on Abu Ma'shar's *Great Introduction to the Science of Astrology*. He also listened to lectures by Gallipus Mixtarabe, a Mozarab who collaborated with Gerard in his translation of the *Almagest*, which they seem to have completed in 1175. Otherwise Gerard appears to have worked alone, for no collaborators are listed in any of his other translations.

Gerard's translations included Arabic versions of writings by Aristotle, Euclid, Archimedes, Ptolemy and Galen, as well as works by al-Kindi, al-Khwarizmi, al-Razi, Ibn Sina, Ibn al-Haytham, Thabit ibn Qurra, al-Farghani, al-Farabi, Qusta ibn Luqa, Jabir ibn Hayyan, al-Zarqallu, Jabir ibn Aflah, Masha'allah, the Banu Musa and Abu Ma'shar. The subjects covered in these translations include 24 works on medicine; 17 on geometry, mathematics, optics, weights and dynamics; 14 on philosophy and logic; 12 on astronomy and astrology; and 7 on alchemy, divination and geomancy, or predicting the future from geographic features.

Gerard may also have published a number of original works, and several have been tentatively attributed to him, including two glosses on medical texts by Isaac Israeli as well as treatises entitled *Geomantia astronomica* and *Theorica Planetarium*. However, it is possible that the latter treatise is a work of John of Seville, whose style Gerard adopted in his translations.

More of Arabic science passed to the West through Gerard than from any other source. His translations produced a great impact upon the development of European science, particularly in medicine, where students in the Latin West took advantage of the more advanced state of medical studies in medieval Islam. His translations in astronomy, physics and mathematics were also very influential, since they represented a scientific approach to the study of nature rather than the philosophical and theological attitude that had been prevalent in the Latin West.

An older contemporary of Gerard, Abu Marwan 'Abd al-Malik ibn Abi'l 'Ala' ibn Zuhr (c. 1092–1162), the Latin Avenzoar, was born in Seville and studied in Cordoba. He belonged to the Banu Zuhr family, which produced five generations of physicians, including two women doctors, who served the Almoravid dynasty in the Maghrib and al-Andalus. Ibn Zuhr served as personal physician to the emir ‘Ali ibn Tashfin (r. 1106–43) in his palace at Marrakech, but because of a misunderstanding he was imprisoned by his patron.

When the Almoravids were overthrown by the Almohads, Ibn Zuhr was restored to favour by the new ruler, Abd al-Mu’min (r. 1145–63), who appointed him as his court physician and personal counsellor, with the rank of vizier. Ibn Zuhr dedicated two medical works to Abd al-Mu’min, the first of which was a treatise on therica, or antidotes to poisons, and the second on dietetics.

Ibn Zuhr’s medical writings were based on the works of Hippocrates and Galen as well as those of his Arabic predecessors and his own researches. His best-known work, *al-Taysir fi’l-mudawat wa’l-’tadbir* (*An Aid to Therapy and Regimen*), was dedicated to his friend Ibn Rushd (Averroës), who had encouraged him to write it. The text, which was in thirty treatises, was translated into Hebrew and Latin and remained in use up until the European renaissance.

The physician and philosopher Abu Bakr Muhammad Ibn Tufayl, known in Latin as Abubacer, was born ca. 1105 at Wadi Ash (Cadiz), north-west of Granada and studied medicine and philosophy at Seville or Cordoba. Working as a physician, he became secretary to the governor of Granada and then to the governor of Ceuta and Tangier. He was then appointed personal physician to the Almohad caliph, Abu Ya’qub Yusuf (r. 1163–84), becoming one of his boon companions. He retired in 1182 and moved to Marrakech in the Maghrib, where he died in 1185.

Ibn Tufayl is best known for his philosophical romance *Hayy ibn Yaqzan* (*Living, Son of the Wakeful*), about a feral youth living alone on a desert island in the Indian Ocean, who through his unaided reason reaches the highest level of knowledge. The novel was translated into Latin in 1671 by Edward Pococke the Younger, under the title *Philosophus Autodidactus.* The first English translation from the Arabic was done in 1708 by Simon Ockley. One of these translations may have inspired Daniel Defoe to write *Robinson Crusoe*, published in 1719. It has been suggested that *Philosophus Autodidactus* influenced Thomas Hobbes, John Locke, Isaac Newton, Gottfried Leibniz and Voltaire.

Ibn Tufayl was the first Andalusian thinker to make use of the works of Ibn Sina, though with some differences, such as his belief that there is no proof that the world is eternal rather than created in time. He also wrote an astronomical thesis, now lost, which is mentioned by his student Abu Ishaq al-Bitruji.

According to al-Bitruji, in this thesis Ibn Tufayl opposed certain aspects of Ptolemaic astronomy, apparently formulating a planetary model that avoided using the epicycles and eccentric circles of Ptolemy.

Ibn Tufayl's researches in astronomy were continued by Abu Ishaq al-Bitruji, the Latin Alpetragius, who flourished in Seville ca. 1190. Al-Bitruji's only known work is his *Kitab fi'l-hay'a* (*Book of Astronomy*), in which he says that he was a student of Ibn Tufayl.

Al-Bitruji acknowledged that Ptolemy's theory gave an exact mathematical description of planetary motion. But he felt that the Ptolemaic model was unsatisfactory since its eccentrics, epicycles, equants and deferents were incompatible with Aristotle's physical concept of the homocentric spheres. He also pointed out a problem involving Aristotle's notion that the Prime Mover imparted motion to the ninth and outermost celestial sphere, and that this then was passed in turn to the inner spheres. If that were the case, he said, then the outer planets should move faster than the inner ones, rather than the other way round.

The *Kitab fi'l-hay'a* was translated into Hebrew and Latin, leading to the spread of al-Bitruji's ideas through much of Europe from the thirteenth century on into the seventeenth. Al-Bitruji's planetary model was used by those who were defending Aristotle's theory of the homocentric spheres against the supporters of Ptolemy's eccentrics and epicycles. Copernicus refers to al-Bitruji in connection with the order of the planets Mercury and Venus in his heliocentric theory of 1543.

Al-Bitruji was an older contemporary of the great Muslim geographer and cartographer Muhammad al-Idrisi (1100–ca. 1165). Al-Idrisi was born in Cueta, on the North African side of the Straits of Gibraltar, and studied in Cordoba. He travelled widely in the Maghrib and al-Andalus and also visited Asia Minor, France and England before moving to Palermo in 1138 on the invitation of Roger II (r. 1130–54), the Norman ruler of the 'Kingdom of the Two Sicilies'.

The Normans had driven the Byzantines from their last footholds in southern Italy in the late eleventh century and then subdued the Arabs in Sicily. When Count Roger I conquered Palermo in 1091 it had been under Muslim domination for nearly two centuries. He reduced the Muslims to the status of serfs except in Palermo, his capital, where he employed the most talented of them as civil servants, so that Greek, Latin and Arabic were spoken in the Norman court and used in royal charters and registers. Under his son Roger II, Palermo became a centre of culture for both Christians and Muslims, surpassed only by Cordoba and Toledo. Beginning under Roger II, and continuing with his successors, the Sicilian court sponsored translations from both Greek and Arabic into Latin.

Roger II was particularly interested in geography, but he was dissatisfied with existing Greek and Arabic geographical works. This led him to write to al-Idrisi, who was already renowned as a geographer, inviting him to his court in Palermo, saying 'If you live among the Muslims, their kings will contrive to kill you, but if you stay with me you will be safe'. Al-Idrisi accepted the offer and lived in Palermo under Roger II and his successor William I (1154–66), after which he returned to Ceuta and passed his remaining days there.

Roger commissioned al-Idrisi to create a large circular relief map of the world in silver, the data for which came from Greek and Arabic sources, principally Ptolemy's *Geography*, as well as travellers and the king's envoys. The silver map has long since vanished, but its features were probably reproduced in the sectional maps in al-Idrisi's Arabic geographical compendium, *Al-Kitab al-Rujari* (*Roger's Book*), also known as *Kitab nuzhat al-mushtaq fi ikhtiraq al-afaq* (*The delight of him who desire to journey through the climates*), which has survived.

The compendium deals with both physical and descriptive geography, with information on political, economic and social conditions in the lands around the Mediterranean and in the Middle East, and is thus a veritable encyclopedia of the medieval world. Al-Idrisi's work was translated into Latin in part in 1619. A Latin translation was published at Paris in 1619, and a two-volume French translation was done in 1830–40, entitled *Géographie d'Edrisi.*

After the death of Roger II al-Idrisi wrote another and larger geographical compendium for King Willam I, entitled *Rawd al-Nas wa-nuzhat al-nafs* (*Pleasure of Men and Delight of Souls*). He also wrote a pharmacological work entitled *Comprehensive Book of the Properties of Diverse Plants and Various Kinds of Simple Drugs.*

Frederick II of Hohenstauffen (r. 1211–50), the Holy Roman Emperor and King of the Two Sicilies, was a grandson of Emperor Frederick I Barbarossa and the Norman king Roger II. Known in his time as *stupor mundi*, 'the wonder of the world', he had been raised from age seven to twelve in Palermo, where he grew up speaking Arabic and Sicilian as well as learning Latin and Greek. When he became emperor in 1211, at the age of fourteen, he turned away from his northern dominions to his Kingdom of the Two Sicilies, where, like his Norman predecessors, who were known as 'baptised sultans', he indulged himself in his harem.

Frederick was deeply interested in science and mathematics, and he invited a number of scholars to his brilliant court, most notably John of Palermo, Master Theodorus and Michael Scot, calling them his 'philosophers'. He subsidised their scientific writings and translations, which included works of Aristotle on physics and logic, some of which he presented in 1232 to the professors at Bologna University. The letter that Frederick sent with the gift told of how he had loved learning since his youth, and of how he still took time from affairs of state to read in his library, where numerous manuscripts of all kinds 'classified in order, enrich our cupboards'.

Frederick's scholarship is evident in his famous book on falconry, *De Arte Venandi cum Avibus*, or *The Art of Hunting with Birds*. This is a scientific work on ornithology as well as a detailed and beautifully illustrated manual of falconry as an art rather than a sport. Frederick acknowledged his debt to Aristotle's *Zoology*, which had been translated by Michael Scot earlier in the twelfth century. But he was critical of some aspects of the work, as he writes in the preface to his manual: 'We have followed Aristotle when it was opportune, but in many cases, especially in that which regards the nature of some birds, he appears to have departed from the truth. That is why we have not always followed the prince of philosophers, because rarely, or never, had he the experience of falconing which we have loved and practiced always.'

One of those with whom Frederick corresponded was the renowned mathematician Leonardo Fibonacci (ca. 1170–after 1240), who had been presented to him when he held court at Pisa about 1225. Leonardo had at that time just completed his treatise on squared numbers, the *Liber quadratorum*, which he dedicated to Frederick, noting 'I have heard from the Podesta of Pisa that it pleases you from time to time to hear subtle reasoning in Geometry and Arithmetic.'

Leonardo was born in Pisa ca. 1170. He writes about his life in the preface to his most famous work, the book on calculations entitled *Liber abbaci*. His father, a secretary of the Republic of Pisa, was around 1192 appointed director of the Pisan trading colony in the city of Bugia (now Bejaia in Algeria). Leonardo was brought to Bugia by his father to be trained in the art of calculating, which he learned to do 'with the new Indian numerals'. Around 1200 he returned to Pisa, where he spent the rest of his days writing the mathematical treatises that made him one of the most important mathematicians of the Middle Ages.

The five works of Leonardo that have survived are the *Liber abbaci*, first published in 1202 and revised in 1228; the *Practica geometriae* (1220–1), on applied geometry; a treatise entitled *Flos* (1225), sent to Frederick II in response to mathematical questions that had been put to Leonardo by John of Palermo at the time of the emperor's visit to Pisa; an undated letter to Master Theodorus, one of the 'philosophers' in the court of Frederick II; and the *Liber quadratorum* (1225). The latter work contains the famous 'rabbit problem': 'How many pairs of rabbits will be produced in a year, beginning with a single pair, if in every month each pair produces a new pair which become productive from the second month on?' The solution to this problem gave rise to the so-called Fibonacci numbers, a progression in which each number is the sum of the two that precede it (e.g., 1, 1, 2, 3, 5, 8, 13, 21, etc.), a mathematical wonder that continues to fascinate mathematicians. Leonardo's sources, where they can be traced, include Greek, Roman, Indian and Arabic works, which he synthesised and, adding to them with his own creative genius, undoubtedly helping to stimulate the beginning of the new European mathematics.

Leonardo dedicated his *Flos* to John of Palermo, whom he also mentions in the introduction to the *Liber quadratorum*. John's only known work is a Latin translation of an Arabic treatise on the hyperbola, which may be derived from a work by Ibn al-Haytham on the same subject.

Master Theodorus, who is usually referred to as 'the Philosopher', was born in Antioch. He served Frederick as secretary, ambassador, astrologer and translator, from both Greek and Arabic into Latin, and he was also the emperor's chief confectioner. One of his works is a translation of an Arabic work on falconry. He served the emperor until the time of his death around 1250, when Frederick regranted to another favourite the estate that 'the late Theodore our philosopher held so long as he lived'.

Theodorus had probably succeeded Michael Scot as court astrologer. Michael was born in the last years of the twelfth century, probably in Scotland, though he might possibly be Irish. Nothing is known of his university studies, but his references to Paris indicate that he may have studied and lectured there as well as in Bologna, where he did some medical research in 1220 or 1221. He may have learned Arabic and some Hebrew in Toledo, where about 1217 he translated al-Bitruji's *On the Sphere*, with the help of Abuteus Levita, a Jew who later converted to Christianity. By 1220 he had completed what became the standard Latin version of Aristotle's *On Animals*, from a ninth-century Arabic version by al-Bitriq, as well as the *De caelo* and the *De anima* with Ibn Rushd's commentaries.

When Leonardo Fibonacci completed his revised version of *Liber abbaci* in 1228 he sent it to Michael, who by that time seems to have entered the service of Frederick II as court astrologer. Michael wrote for the emperor a Latin summary of Ibn Rushd's *De animalibus* as well as a voluminous treatise known in English as *Introduction to Astrology*. The latter work covers every aspect of astrology and divination including necromancy, or conjuring up the spirits of the dead to reveal the future or influence the course of coming events, as well as nigromancy, or black magic, dealing with dark things performed by night rather than by day.

Such was the astonishing variety of the scientific works transmitted between the Muslim Arabic and Christian Latin worlds in the West during the late medieval era, in a cultural interface that extended from the Maghrib to the Two Sicilies.

CHAPTER 14

Incoherent Philosophers

Abu Hamid Muhammed ibn Muhammed al-Ghazali, known in the Latin West as Algazel, did not consider himself to be a philosopher, but rather a jurist and theologian who came to reject rational philosophy.

Al-Ghazali was born in 1058 in Tus in the Persian province of Khorasan, the son of a Sufi, an Islamic mystic. His father died when he was young, leaving him and his brother Ahmad to be cared for by a family friend. When al-Ghazali was twelve he and his brother went to Jurjan to enroll in a madrasa, where he studied religious law for seven years before returning to Tus. Around 1080 he went to Nishapur, the provincial capital, to study theology – *kalam* – with the noted Imam al-Haramayn al-Juwayni. After the death of al-Juwayni in 1085 al-Ghazali became associated with the court of Nizam al-Mulk, the powerful vizier of the Seljuk sultan Jalal al-Din Malikshah, who in 1091 appointed him as professor of religious law at the Nizamiyyah madrasa at Baghdad. He taught there for four years and also made an intensive study of philosophy, including the works of al-Farabi and Ibn Sina as well as those of his Islamic predecessors. As he writes of this in his autobiography, *The Deliverance from Error*: 'By my solitary reading during the hours thus snatched God brought me in less than two years to a complete understanding of the science of the philosophers.'

During al-Ghazali's tenure in Baghdad he wrote a number of philosophical works, most notably *The Incoherence of the Philosophers*. He says in his autobiography that he was led to write this book by the errors and heresies of earlier philosophers from Aristotle to al-Farabi and Ibn Sina, the principal interpreters of Aristotelian ideas in the Islamic world. Referring to Plato and Aristotle, he writes that 'We must therefore reckon as unbelievers both those philosophers themselves and their followers among the Islamic philosophers, such as Ibn Sina, al-Farabi and others; in transmitting the philosophy of Aristotle, however, none of the Islamic philosophers has accomplished anything comparable to the achievement of the two men named.'

Al-Ghazali identified the 'philosophical sciences' as mathematics, logic, natural science, philosophy, theology, metaphysics, politics and ethics. His view was that mathematics and logic were not 'connected with religious matters, either to deny or affirm them'. So far as natural science, philosophy or physics were concerned, his main objections to the theories of the philosophers was that they did not recognise that nature is subject to divine command. 'The basis of all these objections is the recognition that nature is in subjection to God most high, not acting of itself but serving as an instrument in the hands of its Creator. Sun and moon, stars and elements, are in subjection to His Command. There is none of them whose activity is produced by or proceeds from its own essence.'

Al-Ghazali believed that 'most of the errors of the philosophers' occur in theology or metaphysics. He particularly criticised Aristotelian positions of al-Farabi and Ibn Sina, writing that 'They were unable to satisfy the conditions of proof they lay down in logic, and consequently differ much from one another here.' He went on to say that 'The views of Aristotle, as expounded by al-Farabi and Ibn Sina, are close to those of the Islamic writers. All their errors are comprised under twenty heads, on three of which they must be reckoned infidels and on seventeen heretics. It was to show the falsity of their views on these twenty points that I composed *The Incoherence of the Philosophers.*'

Al-Ghazali writes in his autobiography that when he completed his study of the philosophical sciences he was still not satisfied. 'By the time I had done with the science of philosophy – acquiring an understanding of it and marking what was spurious in it – I had realised that this too did not satisfy my aim in full and that the intellect neither comprehends all it attempts to know nor solves all its problems.' He goes on to say that his dissatisfaction with the philosophical sciences led him to the study of mysticism. 'I knew that the complete mystic "way" includes both intellectual belief and practical activity; the latter consists in getting rid of the obstacles in the self and in stripping off its base characteristics and vicious morals, so that the heart may attain to freedom from what is not God and to constant recollection of Him.'

Toward the end of his tenure in Baghdad al-Ghazali underwent a spiritual crisis, feeling that his way of life was too worldly to give him any hope of eternal reward. This led him to abandon his teaching career and leave Baghdad in 1195 to adopt the ascetic life of a wandering Sufi, going first to Damascus and then to Jerusalem. He then made the pilgrimage to Mecca and went on to Medina, after which he returned to Persia before 1099. He continued to live in obscurity until 1106, when Fakhr al-Mulk, vizier of the Seljuk sultan Sanjar, persuaded him to resume teaching at the Nizamiyyah madrasa in Nishapur. Al-Ghazali's second period of teaching lasted for just two years, after which he returned to Tus, where he died in December 1111.

Toward the end of his life al-Ghazali, in a letter to Sultan Sanjar, mentioned that he had written more than seventy works. His major works comprise eight in theology, including *The Deliverance from Error*; six in Sufism; five in philosophy, including *The Incoherence of the Philosophers*; and five in jurisprudence. Most of his works were written in Arabic and a few in Persian. His most important work in Persian is *The Alchemy of Happiness*. This is a shorter version of a four-volume treatise on Sufism in Arabic entitled *The Revival of the Religious Sciences*, which is generally considered to be one of al-Ghazali's greatest works. Here his concept of divine creation has been said to resemble Leibniz's notion of the 'best of all possible worlds', where al-Ghazali writes that 'Everything which God apportions to man ... is ... pure right, with no wrong in it. Indeed, it is according to the necessarily right order, in accord with what must be and as it must be and in the measure in which it must be, and there is not potentially anything more excellent and more complete than it.'

The decline of Arabic science that began in the twelfth century is sometimes attributed at least partly to Al-Ghazali's influence. Nevertheless, Arabic work in mathematics, mechanics and astronomy, at least, remained at a high level long after his time, particularly in Central Asia.

Abu l-Walid Muhammad ibn Ahmad ibn Muhammad ibn Rushd (1126–98), the Latin Averroës, who was from a distinguished family of Cordoban jurists would also have a profound effect on Arabic philosophy. Ibn Rushd, was named for his grandfather, who was *imam* of the Great Mosque and also *qadi*, a position his father also held. He studied theology, law, medicine and philosophy, particularly the works of Aristotle, which he read in Arabic translation.

Ibn Rushd was in Marrakech in 1152, during the reign of the Almohad ruler 'Abd al-Mu'min, when he seems to have made his first astronomical observations. There he met Ibn Tufayl, who would later play an important part in his life by introducing him to Caliph Abu Ya'qub Yusuf. According to al-Marrakushi, the caliph had complained to Ibn Tufayl about his difficulty in reading the works of Aristotle and the need for a commentary to explain them. Ibn Tufayl said that he himself was too old and busy to do the job, and so he recommended Ibn Rushd, who was thus led to begin his monumental series of commentaries on the works of Aristotle.

After the death of Ibn Tufayl, Ibn Rushd became personal physician to Abu Ya'qub Yusuf and was appointed *qadi*, first in Seville, then in Cordoba, and then again in Seville. He retained his posts under Abu Ya'qub Yusuf's son and successor Abu Yusuf Ya'qub al-Mansur (r. 1184–99), though in 1195 the caliph confined him for two years to the town of Lucena, near Cordoba, because orthodox Islamic scholars had condemned his philosophical doctrines. Early in 1198 the caliph lifted the ban and took Ibn Rushd with him to his court at Marrakech. But Ibn Rushd had little time to enjoy his freedom, for he died in Marrakech on 10 December of that year, after which his body was returned to Cordoba for burial.

Most of the philosophical writings of Ibn Rushd can be divided into two groups, his commentaries on Aristotle and his own treatises on philosophy. His commentaries on Aristotle, thirty-eight in number, are of three types, the so-called *Short*, *Middle* and *Long Commentaries*. The *Short Commentaries*, generally considered to be early works, comprise summaries of Aristotle's ideas, usually based on the Greek commentators. The *Middle Commentaries* are usually simplified paraphrases of Aristotle's writings, and are thought to have been written in response to the request of Ibn Ya'qub Yusuf. The *Long Commentaries*, Ibn Rushd's mature works, deal with the entire Aristotelian corpus, beginning with the *Posterior Analytics*, followed by *De nima*, the *Physics*, *De Caelo* and the *Metaphysics*. His commentaries were translated into Latin in the thirteenth century, and influenced some of the leading intellectual figures in Europe at the time, most notably Albertus Magnus and Thomas Aquinas. Thomas Aquinas in particular assimilated the Aristotelianism of Averroës, as he was known in Latin, and worked it into a system of thought that was theologically acceptable to the Catholic Church.

Ibn Rushd's own philosophical works include the *Decisive Treatise on the Harmony between Religion and Philosophy*, the *Exposition of the Methods of Demonstration Relative to the Religious Dogmas and to the Definition of the Equivocal Meanings and Innovations Encountered in the Process of Interpretation and which alter the Truth and Error* and the famous *Incoherence of the Incoherence of the Philosophers.*

The second of these treatises was intended as a sequel to the first, and Ibn Rushd noted that his aim in the two works was 'the examination of the external aspect of the beliefs which the lawgiver [i.e., Muhammad] intended the public to adhere to', as distinct from the false beliefs they had been led into by theologians. He said that by 'external beliefs' he meant those 'without which the faith [of the believer] is not complete'.

The *Incoherence of the Incoherence* was written in opposition to al-Ghazali's attack on the works of al-Farabi and Ibn Sina, the two leading Muslim interpreters of Aristotle. Ibn Rushd, in his defence of Aristotelianism, argued that al-Gazali's attacks on al-Farabi and Ibn Sina were mistaken, besides which their ideas often deviated from those of Aristotle. This was in keeping with Ibn Rushd's effort to resolve the dispute between Islamic theologians and philosophers, as he tried to reconcile apparent contradictions between law and philosophy.

Ibn Rushd's commentaries attempted to restore Aristotle's own ideas in Islamic thought and to supplant the Neoplatonism of al-Farabi and Ibn Sina. He regarded the philosophy of Aristotle as the last word, to the extent that truth can be understood by the human mind.

One of the points on which al-Ghazali had criticised the philosophers in their interpretation of Aristotle, most notably al-Farabi and Ibn Sina, was their denial of the divine creation of the world at some moment in time, for this would have meant that something temporal emerged from the eternal, which is inconceivable. Ibn Rushd quotes al-Ghazali's statement of the arguments of the philosophers: 'At one moment the object of will did not exist, everything remained as it was before, and then the object of will existed. Is this not a perfectly absurd theory.' Al-Ghazali, addressing the philosophers, asks them what is wrong with the notion of divine creation:

> Why do you deny the theory of those who say that the world has been created by an eternal will which has decreed its existence in the time in which it exists, its non-existence lasting until the time it ceases and its existence beginning from the time it begins, while its existence was not willed before and therefore did not happen, and that at the precise moment it began it was willed by an eternal will and so began? What is the objection to this theory, and what is absurd in it?

Al-Ghazali then wonders whether the divine will might not be similar to that of humans, who often decide to do something but delay the implementation of their decision. He gives the example of a man who decides to divorce his wife but does not actually do so until she has committed an offence that gives him the legal basis for his action. As Ibn Rushd puts al-Ghazali's argument:

> In the same way as the actual divorce is delayed after the formula of the divorce till the moment when the condition of someone's entering the house, or any other, is fulfilled, so that the realisation of the world can be delayed after God's act of creation until the condition is fulfilled on which this realisation depends, i.e., the moment when God willed it. But conventional things do not behave like rational things.

Al-Ghazali goes on to suggest that the divine will is actually very dissimilar to that of humans, so that arguments in which the philosophers draw comparisons between the two are invalid. Ibn Rushd ridicules this criticism, saying that the philosophers have tried to demonstrate logically the impossibility of an eternal will being involved in a temporal creation, and that al-Ghazali is absolutely wrong in suggesting that their objection to divine creation is based on intuition rather than on valid arguments.

Ibn Rushd in his mature work rejects the Neoplatonist cosmology of emanation that had been held by al-Farabi and Ibn Sina, in which the heavenly intelligences emanate from the First Being in the outermost celestial sphere as far as the innermost sphere of the moon, where the Active Intellect endows material bodies with their form. He criticises al-Farabi and Ibn Sina for attributing the emanation theory to Aristotle and thus distorting his whole teaching. Roger Arnaldez writes of how Ibn Rushd rejected the Neoplatonist view of emanation in favour of the Aristotelian theory in which 'he explained that the First Mover moves the world not by a sort of attraction, but by his commandment, like a king seated on his throne who has no need himself of moving in order to act'.

Ibn Rushd believed that there can be no essential conflict between philosophy and religion, that is to say, reason and revelation, which he regarded as different avenues to the same truth. He believed that where there seems to be an apparent conflict then careful study of Scripture, that is, the Kuran and the *hadith*, will show that an allegorical interpretation will resolve the difference. 'We affirm definitely that whenever the conclusion of a demonstration is in conflict with the apparent meaning of Scripture, that apparent meaning admits of allegorical interpretation according to the rules for such interpretation in Arabic.'

The conflict between reason and revelation flared up in Western Europe after Ibn Rushd's Aristotelian commentaries were translated into Latin. It was soon realised that some of his ideas, such as the eternity of the world, were contrary to Christian belief. This gave rise to the term 'Latin Averroism', particularly applied to the thirteenth-century philosopher Siger of Brabant. Siger held that the logical conclusions of reason may be contrary to the truths revealed in religion, nevertheless both must be accepted, a notion that came to be called the theory of 'double truth'.

Ibn Rushd accepted Aristotle's planetary model of the homocentric spheres and rejected Ptolemy's theory of eccentrics, epicycles and equants. He writes of his astronomical researches in his commentary on Aristotle's *Metaphysics*, where he expresses his belief that the prevailing Ptolemaic theory is a mathematical fiction that has no basis in reality.

> In my youth I hoped it would be possible for me to bring this research [in astronomy] to a successful conclusion. Now, in my old age, I have lost hope, for several obstacles have stood in my way. But what I say about it will perhaps attract the attention of future researchers. The astronomical science of our days surely offers nothing from which one can derive an existing reality. The model that has been developed in the times in which we live accords with the computations, not with existence.

Aristotle had included fifty-five spheres in his model of the celestial motions. Ibn Rushd says that in his time astronomers set this number at fifty, while he himself used forty-five. But at the same time he wrote: 'As to a profound examination of what is necessarily and really involved in this question, we leave it to those who devote themselves more completely to this art, those who dedicate themselves entirely to it and who concern themselves with nothing else.'

In his commentary on Aristotle's *Physics*, Ibn Rushd attacked Ibn Bajja's theory of motion, specifically the idea that the medium impeded natural motion. Instead he supported Aristotle's theory, in which the velocity of a body is proportional to the force acting on it divided by the resisting force of the medium.

According to Ernest A. Moody, Ibn Rushd was the first to define force as 'the rate at which work is done in changing the kinetic condition of a moving body', and also the first to state 'that the effect and measure of a force is change in the kinetic condition of a materially resistant mass'. These are perhaps some of the clearest statements about the effect of force on motion before the Scientific Revolution of the seventeenth century. Ibn Rushd also seems to have asserted that bodies have an inherent resistance to a change in their state of motion, the concept that came to be known as inertia. But he attributed this inertia only to the celestial spheres, to explain why they do not move with infinite speed when they are set in motion by the Prime Mover, as they would according to Aristotle's theory, for there would otherwise be no resistance to slow them down in the heavens.

One of Ibn Rushd's Aristotelian commentaries, the *Epitome of the Parva Naturalis*, supports Aristotle's intromission theory of light, in which vision is due to light passing from the luminous object to the eye, rather than the other way round, as in the extramission theory. One passage describes the transmission from the object through the air and the various coatings of the eye. 'We maintain that the air, by means of light, receives the forms of objects first and then conveys them to the external coat of the eye, and the external coat conveys them to the remaining coats, until the movement reaches the innermost coat behind which the common sense is located, and the latter perceives the form of the object.' Another passage identifies the retina as the basic photosensitive organ in the eye, a notion that was revived by the anatomist Felix Platter (1536–1615).

> The innermost of the coats of the eye [i.e., the retina] must necessarily receive the light from the humors of the eye, just as the humors receive the light from the air. However, inasmuch as the perceptive faculty resides in the region of this coat of the eye, in the part which is connected with the cranium and not in the part facing the air, these coats, that is to say the curtains of the eye, therefore protect the faculty of the sense by virtue of the fact that they are situated in the middle between the faculty and the air.

Aristotle's *Politics* was not available to Ibn Rushd, and so instead he wrote a commentary on Plato's *Republic* to express his ideas on political science. This is to some extent a paraphrase of the *Republic*, while at the same time it quotes Plato on a number of topics and analyses some of his arguments. One particularly interesting passage gives Ibn Rushd's views on law, prophecy and philosophy. 'What the laws existing in this time of ours assert … is [that the end of man is doing] what God, may he be exalted, wills, but that the only way of knowing this matter of what it is God wills of them is prophecy.'

Ibn Rushd's major work on medicine is his *al-Kulliyyat* (*Generalities*), which is based mainly on the writings of Ibn Sina, with occasional references to Hippocrates. It is divided into seven books, entitled 'Anatomy of Organs', 'Health', 'Sickness', 'Symptoms', 'Drugs and Foods', 'Hygiene' and 'Therapy'. Two Hebrew translations of *al-Kulliyyat* are known, the translator of one of them identified as Solomon ben Abraham ben David. A Latin translation, entitled *Colliget*, was made in Padua in 1255 by a Jewish scholar named Bonacosa, the first printed edition of which was published at Venice in 1482. A passage in the *Colliget* gives Ibn Rushd's explanation of the visual process, particularly concerning what David C. Lindberg describes as 'the reception of forms in the eye and their subsequent transmission to the seat of consciousness in the brain'. As Ibn Rushd writes in this passage:

> And you know that the sense of light receives the forms of things in this manner. First air, when light mediates, receives the forms of things and transmits them to the anterior tunic [the cornea], which conveys them to the other tunics until this motion reaches the final tunic [the retina], behind which is situated the common sense, which apprehends the forms.

Ibn Rushd's *al-Kulliyyat* and Ibn Zuhr's *al-Taysir* (*An Aid to Therapy and Regimen*), were meant to constitute a comprehensive medical textbook, and some Latin editions contain both treatises bound together as a single book, which in some places supplanted Ibn Sina's *Canon*.

Ibn Rushd wrote a commentary on Ibn Sina's *Poem on Medicine*, which was translated into Hebrew prose by Moses ben Tibbon in 1260. The following year a rendering into Hebrew verse was completed by Solomon ben Ayyub ben Joseph. A Latin translation was done in the early 1280s, and a printed edition was published at Venice in 1484. Ibn Rushd also wrote a *Treatise on Theriac* (*Antidote to Poisons*), which was translated into Latin by Andrea Alpago, who also did a revised Latin translation of his commentary on Ibn Sina's *Poem on Medicine*.

Ibn Rushd also complained about discrimination against women, which he felt was one of the most serious problems in Muslim society. 'Our society allows no scope for the development of women's talents. They seem to be destined exclusively to childbirth and the care of children, and this state of servility has destroyed their capacity for larger matters. It is thus that we see no women endowed with moral virtues, they live their lives like vegetables, devoting themselves to their husbands. From this stems the misery that pervades our cities, for women outnumber men by more than double and cannot procure the necessities of life by their own labors.'

Ibn Rushd's writings deeply influenced Maimonides and through him other Jewish scholars, who read his works in Arabic. By the beginning of the thirteenth century Ibn Rushd was considered to be the outstanding interpreter of Aristotle and his works were translated into Hebrew. By the end of that century nearly half of his commentaries on Aristotle had been translated from Arabic into Latin, so that in the West Averroës came to be known as the Commentator.

CHAPTER 15

Maragha and Samarkand: Spheres Within Spheres

Islamic historical writing reached a peak with the work of Ibn Khaldun (1332–1406), whose *Muqaddimah* (*An Introduction to History*) was described by Arnold Toynbee as ‘undoubtedly the greatest work of its kind that has ever been created by any mind in any time or place.’

Ibn Khaldun was born in Tunis and was educated there and in Fez. After completing his education he moved in turn to Fez, Granada, Algeria, Tunis and Cairo, where he arrived on 6 January 1383. He spent the rest of his life in Egypt, except for periods of travel in Syria and Palestine as well as a pilgrimage to Mecca. He served as a *qadi*, or judge, under the Mamluk sultan al-Zahir Barquq and his son and successor Faraj. He accompanied Faraj in 1401 on an expedition to Damascus, which at the time was being besieged by a Mongol army under Timur, known in the West as Timur. Ibn Khaldun met with Timur outside Damascus and helped arrange for the Mamluk prisoners of the Tatars to be pardoned before the city was captured and sacked.

Ibn Khaldun devotes Chapter 6 of the *Muqaddimah* to ‘The various kinds of science; the methods of instruction; the conditions that obtain in these connections.’ He begins by writing that ‘God distinguished man from all the other animals by an ability to think which He made the beginning of human perfection and the end of man’s noble superiority over existing things.’ He goes on to say that though science had virtually disappeared in al-Andalus and the Maghrib it still flourished in the Muslim East, nourished by the civilisation that had flourished there since antiquity. ‘These cities have never ceased to have an abundant and continuous civilisation, and the tradition of scientific instruction has always persisted in them.’

During the Mamluk period Damascus flourished as a centre of learning and science. Caliph al-Ma'mun had ordered his astronomers to make observations in Damascus as well as in Baghdad, a project that produced *al-Zij al-Mumtahan* (*The Verified Tables*), which were widely used by Arabic astronomers for many years.

The mathematician and astronomer Sharaf al-Din al-Muzaffar ibn Muhammad ibn al-Muzaffar al-Tusi likely taught at Baghdad around 1165. Al-Tusi's main achievement in mathematics is a treatise on algebra in which he found numerical solutions of cubic equations. His astronomical observations were made using an instrument of his own invention, a simplified linear version of the astrolabe known as 'al-Tusi's staff', which he claimed could be built in about an hour. Although less accurate than the circular astrolabe, al-Tusi's staff, which he described in several treatises, sufficed to measure the coordinates of the celestial bodies, the time of day, and the direction of Mecca, which was good enough for most mosque astronomers. He also taught a number of young men who became distinguished astronomers. One of his pupils was Kamal al-Din ibn Yunus (d. 1243), who in turn would teach the famous religious scholar Nasir al-Din al-Tusi.

After the fall of the 'Abbasid dynasty two important astronomical observatories were founded in Central Asia by Mongol rulers. The three most renowned were at Maragha and Tabriz in Persia and at Samarkand, in what is now Uzbekistan. A number of Arabic as well as Persian astronomers, physicists and mathematicians made important advances at these observatories during the two centuries following the Mongol conquest of Baghdad, which has led at least one modern historian to describe that era as the golden age of Islamic science.

The Maragha observatory was founded in 1259 by the Ilkhanid Mongol ruler Hulagu Khan, grandson of Genghis Khan. The first director of the observatory and its centre of learning, which included a madrasa and a library, was the Persian astronomer and mathematician Nasir al-Din al-Tusi (1201–74). The actual construction of the observatory and its instruments was directed by Mu'ayyad al-Din al-'Urdi of Damascus.

The astronomer, astrologer and craftsman (today's engineer) Mu'ayyad al-Din al-'Urdi was born near Aleppo early in the thirteenth century, and later went to live in Damascus, after the Mongols invaded Syria. While in Damascus he made astronomical observations and also repaired and extended the city's water supply system. After the Mongols conquered Damascus in 1260, he managed to escape the carnage by asserting his usefulness as an astrologer and travelled to Maragha in Persia, where he died around 1266.

Al-'Urdi wrote a manual on the instruments he designed and built for the Maragha observatory. He also wrote a treatise devoted to the reform of Ptolemaic astronomy. Entitled simply *A Book on Astronomy*, it apparently is one of the first Arabic works to offer an alternative to the Ptolemaic epicycle theory.

One of his mathematical methods and the theory that helped to inspire the work of Copernicus, known as 'Urdi's lemma, is a way of representing the epicylical motion of the planets without using Ptolemy's method. 'Urdi's lemma was used by his colleagues and successors at the Maragha observatory, as well as by subsequent astronomers up to and including Copernicus. As al-'Urdi describes his method, stating his lemma in the last sentence:

> But when the center of the epicycle moves with the two motions that we will describe the resultant uniform and composite motion will look as if it is simple with respect to the center of the equant… Every straight line upon which we erect two straight lines on the same side so that they make two equal angles with the [first] line, be they alternate or interior, if their edges are connected, the resulting line will be parallel to the line upon which they are erected.

Hulagu's deed of foundation gave the observatory financial independence, so that it survived his death in 1265 and continued in operation until 1316. During that time at least eighteen astronomers are known to have worked at Maragha, including one from the Maghrib and another from China. The instruments that they used included a mural quadrant with a radius of more than 60 feet, graduated to read minutes of arc. These instruments were used by Nasir al-Din al-Tusi and his staff to compile the *Zij-i Ilkhani*, the Ilkhanid astronomical tables, which were completed in 1272 under Hulagu's successor Abaqa Khan.

Nasir al-Din al-Tusi also wrote a book for the general reader called *Tadhkira fi 'ilm al-hay'a* (*Memoirs of Astronomy*), which described Ptolemaic concepts such as the epicycle theory and introduced new planetary models. One of his innovations was the so-called 'Tusi couple', which has one sphere rolling inside another to give a combination of two circular motions.

What the Tusi couple amounts to is a small sphere rolling inside another sphere double its diameter, with the inner and outer spheres moving in opposite directions. If the inner sphere rolls at twice the speed of the outer one, then a point on the periphery of the inner sphere traces out a straight line coinciding with a diameter of the outer sphere. Al-Tusi was in this way able to represent an oscillating linear motion as the combination of two circular motions at constant velocity, thus holding true to the Aristotelian dictum that all celestial motion should be uniformly circular.

Besides his astronomical writings al-Tusi wrote numerous works on philosophy, ethics, theology, logic, mathematics, mineralogy, medicine, alchemy and astrology, plus a treatise on geomancy.

One of Al-Tusi's main influential philosophical works is a commentary on the last work of Ibn Sina, with whom he differed on a number of points, such as on the nature of space and whether the universe is created by God. His best-known ethical work is *Akhlaq-i nasiri* (*Nasirean Ethics*), where, according to Seyyid Hossein Nasr, 'he expounds a philosophical system combining Islamic teachings with the ethical theories of the Aristotelians and, to a certain extent, the Platonic traditions ... For centuries it has been the most popular ethical work among the Muslims of India and Persia.'

Al-Tusi's *Tajrid* (*Catharsis*) is the principal source book of Shi'ite theology. The most important of his five works on logic, *Asas al-iqtibas* (*Foundations of Inference*), is described by Nasr as 'one of the most extensive of its kind ever written, surpassed only by the section on logic of Ibn Sina's *al-Shifa'*.

The mathematical treaties of al-Tusi include a number of recensions on the works of the Greek mathematicians and astronomers, including Euclid, Archimedes, Apollonius, Aristarchus and Ptolemy. He also wrote many original works in mathematics, most notably *Kashf al-qina fi asrar shakl al-qita* (*Book of the Principle of Transveral*), which was translated into Latin and perhaps influenced Regiomontanus. His *Shakl al-qita* is described by Nasr as 'the first in history on trigonometry as an independent branch of pure mathematics'.

Al-Tusi's most important mineralogical work is his *Tansuqnamah-yi Ilkhanid* (*The Ilkhanid Treatise on Mineralogy*), written in Persian. The book is divided into four chapters, the first on the nature of compounds according to the Aristotelian theory of the four elements; the second on jewels, particularly the medical and occult properties of rubies; the third on metals and the alchemical theory of their formation; and the fourth on perfumes. According to Nasr, this work is 'one of the major sources of Muslim mineralogy and is valuable as a source of Persian scientific vocabulary in this field.'

The principal medical writings of al-Tusi are his *Qawanin al-tibb* (*Principles of Medicine*) and his commentary on Ibn Sina's *Qanun*, along with his letters to various physicians. According to Nasr: 'Al-Tusi's view of medicine was mainly philosophical; and perhaps his greatest contribution was in psychosomatic medicine, which he discusses, among other places, in his ethical writings, especially *Akhlaq-i nasiri*.'

Al-Tusi's works on astronomy and mathematics influenced his colleagues at the Maragha observatory, beginning with Muhyi al-Din al-Maghribi (d. ca. 1290) and Qutb al-Din al-Shirazi (1236–1311), and through later transfers of knowledge, through scholars and over the years, subsequent astronomers in both the East and the West.

As his last name indicates, the family of Muhyi al-Din most likely came from the Maghrib, though we do not know whether he was born there or not. He first studied religious law in the Maghrib and then moved to Aleppo, where he served as court astrologer to the Ayyubid sultan al-Nasir II. By his own testimony, he escaped death when the Mongols conquered Syria by simply telling them that he was an astrologer. He then went to work with Nasir al-Din al-Tusi at the Maragha observatory, where he is known to have made observations during the period 1260–65. His extant manuscripts include a *Compendium of the Almagest* and numerous other works in astronomy and mathematics, the latter including recensions on the works on the *Elements* of Euclid, the *Conics* of Apollonius, the *Spherics* of Theodosius and the *Spherics* of Menelaus. His own mathematical writings include a *Treatise on the Calculation of Sines*, in which he derived an original method for computing the sine of one degree.

Qutb al-Din al-Shirazi took his name from the Persian city of Shiraz, where his father, Mas'ud al-Qadharuni, was a physician and ophthalmologist at the Muzaffari hospital. When Mas'ud died Qutb al-Din was only fourteen, but he was mature enough to take over his father's duties at the hospital, where he worked for the next ten years. He then left the hospital to devote himself full time to his studies, travelling widely to study Ibn Sina's *Qanun* and philosophical works with distinguished teachers in Khorasan, Iraq and Anatolia.

Around 1262 al-Shirazi went to Maragha to study astronomy, mathematics and philosophy with Nasir al-Din al-Tusi, who later saw him as a rival and expelled him from the observatory. Al-Shirazi then went to Tabriz, where, under the patronage of the Ilkhanid Mongol ruler Ghazzan Khan and his successor Uljaytu, he founded an observatory that became the successor to the one at Maragha.

Al-Shirazi improved some of the details of the 'Urdi lemma. His major astronomical work is *Nihayat al-idrak fi dirayet al-aflak* (*The Limit of the Understanding of the Knowledge of the Heavens*), which starts with the statement, obviously referring to al-'Urdi, that 'one of the learned men of the moderns here, who is versed in this discipline [astronomy] had said'. He then gives a detailed paraphrase of al-'Urdi's lunar model, which then became the basis for his own improved theory of the moon's motion.

Al-Shirazi's *Nihayat* also has sections on mechanics, optics, meteorology, geography, geodesy and cosmography. He supplemented this with a work entitled *The Royal Gift of Astronomy*, which was the subject of commentaries by later Arabic astronomers, most notably Ali al-Qushji. Another of his works is entitled *A Book I have Composed on Astronomy, But Do Not Blame Me.*

Al-Shirazi is also renowned for his medical writings, particularly his five-volume commentary on the *Qanun* of Ibn Sina, whom he defended against the attacks of the theologians. His other medical works include a *Treatise on Leprosy*, and a *Treatise on the Explanation of the Necessity of Medicine and of the Manners and Duties of Physicians.*

Al-Shirazi's principal philosophical work is his *Pearls of the Crown, the Best Introduction to Wisdom*, a five-volume tome dealing with the classification of the sciences, with additional sections on philosophy, logic, natural science, philosophy, mathematics, music, ethics, theology and sufism. Historians of philosophy would, however, perhaps consider his commentary on Suhrawadi's text *hikmat al-ishraq* as al-Shirazi's most important philosophical work.

One of Al-Shirazi's most brilliant students at Tabriz was Kamal al-Din al-Farisi (1267–1319), whose last name is derived from his birthplace, the Persian region of Fars. At al-Shirazi's suggestion, al-Farisi wrote a commentary on the optical works of Ibn al-Haytham, entitled *Tanqih al-Manazir*, which he then followed with his own treatise on the science of light, entitled *Revision of Optics.*

Al-Farisi, in his *Tanqih*, clearly states the intromission theory of vision as it appears in Ibn al-Haytham's optics: 'All this being so, the light shining from the self-luminous body into the transparent air therefore radiates from every part of the luminous body facing that air; and the light in the illuminated air is continuous and coherent; and it issues from every point on the luminous body that can be imagined to extend in the air from that point.'

Al-Farisi made several advances on the researches of Ibn al-Haytham, most notably in his theory of the rainbow. Here he used a hollow glass sphere filled with water as an analogue for a raindrop. His studies led him to conclude that the rainbow is due to a combination of refraction and internal reflection of sunlight in the individual drops of water suspended in the air after a rainfall. In the primary rainbow, according to his theory, the light enters the drop and is internally reflected once before leaving, undergoing refraction on entry and departure, while in the secondary bow there are two internal reflections. The colours are due to the refractions, with their order from red to blue inverted in the secondary bow due to the second internal reflection. He gives a clear description of the inverted order of the colours in the two arcs of the rainbow in his *Tanqih*:

> If there are a great many drops of water massed in the air, these, arranged in a circle – each drop giving one of the images mentioned according to

> its size – produce the image of two arcs, as one may see: the small one is red on its exterior circumference, then yellow, then blue. The same colors appear in inverse order on the superior arc, hiding what is behind it by the colors and lights that appear in it. The air between the two arcs is darker than the air above and below them, because the portions between the two arcs are screened from the light of the sun.

The Turkish historian Mustafa Nazif has concluded that al-Farisi published his theory of the rainbow at least a decade before Dietrich of Freiburg, whose researches on the same subject date to the years 1304–11 and led him to the same conclusion. Dietrich refers to the optical works of Ibn al-Haytham but he does not mention the writings of al-Farisi, which were never translated into Latin.

A highly distinguished muwaqqit, or specialised astronomer, of the fourteenth century was ‘Ala’ al-Din Abu’l-Hasan ‘Ali ibn Ibrahim ibn al-Shatir (ca. 1305–ca. 1375) of Damascus. Ibn al-Shatir’s father died when he was six and he was then brought up by his grandfather, who taught him the craft of inlaying ivory. When he was about ten he travelled to Cairo and Alexandria to study astronomy, in the course of which he was inspired by the work of Abu ‘Ali al-Marrakushi, who had in Cairo around 1280 written a compendium of mathematical astronomy and mathematical instruments.

After the completion of his studies Ibn al-Shatir returned to Damascus, where he was appointed muqqawit of the Umayyad Mosque. His principal duties were to determine the time intervals for the five daily occasions of prayer, as well as the dates when the holy month of Ramadan began and ended, while he also constructed astronomical instruments and made observations and calculations to compile astronomical tables.

Ibn al-Shatir’s first set of tables, which have not survived, apparently used his observations together with the standard Ptolemaic model to compute the entries for the sun, moon and planets. But in a later work, *Nihayat al-Sul fi Tashih al Usul* (*The Final Quest Concerning the Rectification of Principles*), he developed a planetary model that varied significantly from that of Ptolemy and was in fact far closer to those of Copernicus, which he then used to produce a new set of tables in a work called *al-Zij al-jadid* (*The New Planetary Handbook*).

Ibn al-Shatir’s new planetary model used secondary epicycles rather than the equants, eccentric deferents and epicycles employed by Ptolemy, his motive being to have the planets moving in orbits composed of uniform circular motions rather than to improve the agreement of his theory with observation. His model improved on the Ptolemaic model, at least with regards to correspondence and observations, so far as the sun was concerned, but in the case of the moon it was clearly superior.

There is no evidence that any Arabic astronomer after Ibn al-Shatir formulated new planetary motions differing from the Ptolemaic model. His *al-Zij al-jadid* continued to be used in Damascus for several centuries, and it was the subject of some commentaries and revisions, one of which adapted it for use in Cairo. The latter was so popular that a commentary on it was published in Cairo in the mid-nineteenth century. Studies by historians of science beginning in 1957 have shown that the lunar model used by Ibn al-Shatir was essentially that same as the one employed by Copernicus in 1543, although research has not revealed the details of how in the course of two centuries the new astronomical theory made its way from Damascus to Italy.

The observatory at Samarkand was founded in 1425 by the Timurid khan Ulugh Begh, grandson of Tamerlane. The observatory was erected on the same site where Ulugh Begh had four years earlier built a madrasa, to which he had added a school for the higher study of science and mathematics. Ulugh Begh's planetary tables, the *Zij-i Sultani*, were published in 1438 and continued to be used for centuries afterwards. He ran his *waqf*, or religious endowment, until 1449, when he was assassinated by his son. Ulugh Begh's observatory closed a few years afterwards, with a glittering record of accomplishments despite its relatively brief lifetime.

The principal astronomer at the Samarkand observatory during its early years was Jamshid al-Kashi (d. 1429), from Kashan in northern Persia. Al-Kashi's principal astronomical work is the *Zij-i Khaqani*, a revision of the *Zij-i Ilkhani* of Nasir al-Din al-Tusi, to which he added trigonometric tables and descriptions of a number of different calendars that had been used in Central Asia, including those of the Uighur Turks and the Ilkhanid Mongols. Another of his astronomical works, *The Stairway of Heaven*, is an attempt to measure the distance and sizes of the planets. Other treatises describe the astronomical instruments he used in his observations, some of them his own inventions.

Al-Kashi's best-known mathematical work is *Miftah al-hisab*, an encyclopedia of elementary mathematics. He also wrote two other mathematical treatises in connection with his researches in astronomy, where his method of approximation in calculating precise trigonometric tables anticipates the work of later European mathematicians.

When al-Kashi died in 1429 he was succeeded as chief astronomer by Qadizadeh al-Rumi (ca. 1364–ca. 1436). Qadizadeh was born and educated in Bursa, the first capital of the Ottoman Turks, in north-western Asia Minor. He travelled to Samarkand and presented himself to Ulugh Begh, who in 1421 appointed him head of his newly founded madrasa. After he became head of the observatory he wrote a number of treatises on astronomy and mathematics, including a commentary on Shams al-din Samarqandi's *ashkal al-ta'*, which is a commentary on books one and two of Euclid's *Elements.*

A student of Qadizadeh, Mulla Fath Allah al-Shirwani, wrote a commentary on al-Tusi's *Tadhkira* during the reign of Ulugh Begh. Here, in George Saliba's paraphrase, al-Shirwani describes how Ulugh Begh himself would often sit in on Qadizadeh's lectures:

> ... al-Shirwani ... attests to the fact that he was a student of Qadizadeh at the Ulugh Begh school in Samarqand. The author goes on to describe the actual conduct of the class, where the students were studying Nisaburi's commentary on Tusi's *Tadhkira*, under the professorship of Qadizadeh and in the presence of Ulugh Begh himself. In the same text a reference is made to Ulugh Begh's visit to the said school two or three times a week, where he would listen to the students reading Nisaburi's text and interrupted them at critical points to ask for spontaneous responses to the subtle difficulties raised in the text; then he would add comments of his own to their responses.

When Qadizadeh died around 1436 he was succeeded as head astronomer by Ali al-Qushji (ca. 1402–74). Ali was born in Samarkand, taking the name of Qushji, or Bird-Man, since in his youth he had been Ulugh Begh's falconer. He subsequently served as Ulugh Begh's ambassador to China. After becoming chief astrologer he supervised the completion of Ulugh Begh's astronomical tables, the *Zij-i Sultani.* These tables were first written in Persian and soon afterwards translated into Arabic and Turkish.

Al-Qushji left Samarkand soon after Ulugh Begh's death. He later went to Istanbul as chief astronomer for the Ottoman sultan Mehmet II (r. 1451–81), known as Fatih, or the Conqueror, in honour of his capture of Constantinople in 1453. Al-Qushji's writings include two treatises dealing with the solution of the problems posed by the Ptolemaic models, one for the moon and the other for Mercury.

Mehmet's conquest of Constantinople ended the Byzantine Empire, which had lasted for more than a thousand years after Constantine the Great shifted his capital to Byzantium.

The Ottoman Empire itself would last for 470 years after Mehmet's conquest of Constantinople, which as Istanbul would become the new Ottoman capital. At its peak the Ottoman Empire would include most of south-eastern Europe as well as the parts of the Middle East and narrow areas of the North African coast, but after the Turks failed to take Vienna in 1683 the tide of conquest turned.

CHAPTER 16

Arabic Science and the European Renaissance

By the end of the twelfth century many of the important extant works of Greek science had been translated from Arabic to Latin, along with commentaries and original works of many Islamic, as well as Christian, Jewish and Sabian scholars and scientists. The assimilation of Graeco-Arabic science and philosophy at the first European universities sparked a cultural renaissance that began in the twelfth century and lasted until the middle of the following century. This led to the flowering of what we recognise as modern European science, beginning with the studies of Robert Grosseteste (ca. 1168–1253) and his followers at the universities of Oxford and Paris.

Grosseteste, who had been educated at Oxford and later became chancellor of the university, was the leading figure in the rise of the new European philosophy of nature, which although primarily based upon Aristotelianism, differed from some of Aristotle's doctrines right from the beginning. Although Aristotle's works formed the basis for most non-medical studies at the new European universities, some of his ideas in natural philosophy and the eternity of the cosmos, particularly as interpreted in commentaries by Averroës (Ibn Rushd), were strongly opposed by Catholic theologians.

Grosseteste believed that the study of optics was the key to an understanding of nature, and this gave rise to his Neoplatonic 'metaphysics of light'. He believed that light is the fundamental corporeal substance of material things and produces their spatial dimensions, as well as being the first principle of motion and efficient causation. According to his optical theory, light travels in a straight line through the propagation of a series of waves or pulses, and because of its rectilinear motion it can be described geometrically. Grosseteste called this theory the 'multiplication of species'. Grosseteste does not seem to have been aware of Alhazen's theory, in which every point in a luminous object emits radiation that propagates rectilinearly. He believed that the 'multiplication of species' could be used to explain the propagation of any disturbance, be it light, sound, heat, mechanical action or even astrological influence. Thus he thought that the study of light was of crucial importance for an understanding of nature. He also believed that light, by which he meant not only visible radiation but the divine emanation as well, was the means by which God created the universe, and that through it soul and body interacted in man.

One of Grosseteste's most interesting optical works is his treatise on *The Rainbow*, in which he broke with Aristotelian theory by holding that the phenomenon was due to refracted rather than reflected light. Although his theory was incorrect, he posed the problem in such a way that investigations by those who followed after him approached closer to the true solution through criticising his efforts. His work on the rainbow inspired some verses written about 1270 by the French poet Jean de Meun in his continuation of Guillaume de Lorris' *Romance of the Rose*. These are in Chapter 83, where *Nature explains the influence of the heavens*, in which the poet mentions the *Optics* of Alhazen:

> ...An optics book
> Was written by Alhazen, of the line
> Of Huchain, which none but fools neglect.
> He who would well this rainbow understand
> Should study this, and he should be, besides
> A good observer and a careful judge
> And learned in nature and geometry...

Grosseteste's efforts in framing a new philosophy of nature were continued by Albertus Magnus (ca. 1200–80). Albertus played a crucial role in reviving Aristotle and making his philosophy of nature acceptable to the Christian West. The main problem involved in the Christian acceptance of Aristotle was the conflict between faith and reason, particularly in the Averroist interpretation of Aristotelianism with its determinism and purely Aristotelian in its notion of the eternity of the cosmos. Albertus sought to resolve this conflict by regarding Aristotle as a guide to reason rather than an absolute authority, saying that where Aristotle conflicted with either revealed religion or observation then he must be wrong. Albertus held that natural philosophy and theology often spoke of the same thing in different ways, and so he assigned to each of them its own realm and methodology, assured that there could be no contradiction between reason and revelation.

The most brilliant of Albertus' students was Thomas Aquinas (ca. 1225–74), who came from Italy to study with him, either in Paris or Cologne. Aquinas, like Albertus, tried to resolve the conflict between theology and philosophy, holding that there could be no real contradiction between revelation and reason. Arguing against those who said that natural philosophy was contrary to the Christian faith, he writes in his treatise on *Faith, Reason and Theology* that 'even though the natural light of the human mind is inadequate to make known what is revealed by faith, nevertheless what is divinely taught to us by faith cannot be contrary to what we are endowed with by nature. One or the other would have to be false, and since we have both of them from God, he would be the cause of our error, which is impossible.'

One of the works of Averroës, his commentary on the *Physica* of Aristotle, attacked the theory of Avempace (Ibn Bajja) that motion in a vacuum would be at finite speed, rather than infinitely fast, as Aristotle had maintained. Aquinas argued against Aristotle and Averroës in supporting Avempace's theory, without mentioning his name. He presented Avempace's theory that motion through a vacuum would be finite, the moving body passing from one point of the void to the next in finite intervals of time. Thenceforth the idea of motion in a void gained acceptance among European thinkers.

Aquinas persuaded the Dominican monk William of Moerbeke (ca. 1220–before 1286) to complete the translation of Aristotle's works directly from the Greek. Moerbeke says that he took on this task 'in spite of the hard work and tediousness which it involves, in order to provide Latin scholars with new material for study'.

Moerbeke's translations included some of the writings of Aristotle, commentaries on Aristotle, and works of Archimedes, Proclus, Hero of Alexandria, Ptolemy and Galen. The popularity of Moerbeke's work is evidenced by the number of extant copies of his translations, including manuscripts from the thirteenth to fifteenth centuries, printed editions from the fifteenth century onwards, and versions in English, French, Spanish and even modern Greek done from the fourteenth century through the twentieth. His translations led to a better knowledge of the actual Greek texts of several works, and in a few cases they are the only evidence of lost Greek texts, such as that of Hero's *Catoptrica.* His translations of Archimedes were particularly influential in the development of European mathematical physics in the early renaissance.

Meanwhile, translations were still being made from Arabic into Latin in the thirteenth century. Some of these were done under the patronage of King Alfonso X (1221–84) of Castile and Leon, known in Spanish as el Sabio, or the Wise. Alfonso's active interest in astrology led him to sponsor translations of Arabic works in astronomy and astrology, including a new edition of the *Toledan Tables* of the eleventh-century Cordoban astronomer al-Zarqallu. This edition, known as the *Alfonsine Tables*, included some new observations but retained the Ptolemaic system of eccentrics and epicycles.

One of Grosseteste's most renowned disciples was Roger Bacon (ca. 1219–92), who acquired his interest in natural philosophy and mathematics while studying at Oxford. He received an MA either at Oxford or Paris, around 1240, after which he lectured at the University of Paris on various works of Aristotle. He returned to Oxford around 1247, when he met Grosseteste and became a member of his circle.

Bacon appropriated much of Grosseteste's 'metaphysics of light' with its 'multiplication of species', as well as his mentor's emphasis on mathematics, particularly geometry. In his *Opus maius* Bacon states that 'in the things of the world, as regards their efficient and generating causes, nothing can be known without the power of geometry', and he also says that 'Every multiplication is either according to lines, or angles or figures'. His ideas on optics also repeat those of Grosseteste. Unlike Grosseteste, he was not only aware of Alhazen's work but wrote a commentary on his *Optics*, which influenced his own ideas.

Bacon, in his commentary on ibn al-Haytham – particularly al-Haytham's theory of the eye as a spherical lense – went beyond what Grosseteste had done basing his own anatomical descriptions on those of Hunayn ibn Ishaq and Avicenna. Bacon used his scientific method to study the rainbow, where he improved on Grosseteste's theory in his understanding that the phenomena was due to the action of individual raindrops, though he erred in rejecting refraction as part of the process.

Other works by Bacon include the *Epistola de secretis operibus artis et naturae et de nullitate magiae*, which describes wonderful machines such as self-powered ships, submarines, automobiles and aeroplanes, though it has to be said that many historians believe this to be fantasy. He writes that 'cars can be made so that without animals they will move with unbelievable rapidity... Also flying machines can be constructed so that a man sits in the midst of the machine revolving some engine by which artificial wings are made to flap like a flying bird ...'

Levi ben Gerson (1288–1344) was a Jewish polymath who wrote books on astronomy, physics, mathematics and philosophy, as well as commentaries on the Bible and the Talmud. His greatest work is his *Milhamot Adonai*

(*The Wars of the Lord*), a philosophical treatise in six books, the fifth of which is devoted to astronomy. Here Levi presents his model of the universe, based on several Arabic sources, principally al-Battani, Jabir ibn Aflah and Ibn Rushd. His model differed in important respects from that of Ptolemy, whose theories did not always agree with observations made by Levi. This was particularly so in the case of Mars, where Ptolemy's theory had the apparent size of the planet varying by a factor of six, while Levi's observation found that it only doubled. The instruments used by Levi included one of his own invention, the 'Jacob's Staff', a device to measure angles in astronomical observations. He also employed the camera obscura, an invention of Alhazen, which he used in observing eclipses and in determining the eccentricity of the sun's orbit. Levi's astronomical work was influential in Europe for five centuries, and his Jacob's Staff was used for maritime navigation until the mid-eighteenth century.

Another area in which the new European science developed was optics, the study of light, which had begun at Oxford with the work of Robert Grosseteste and Roger Bacon. The first significant advance beyond what they had done was by the Polish scholar Witelo (b. ca. 1230–35–d. after ca. 1275). Witelo's best known work is the *Perspectiva*, which is based on the works of Robert Grosseteste and Roger Bacon as well as those of Alhazen, Ptolemy and Hero of Alexandria. It would seem that the *Perspectiva* was not written before 1270, since it makes use of Hero's *Catoptrica*, the translation of which was completed by William of Moerbeke on 31 December 1269.

Witelo adopted the 'metaphysics of light' directly from Grosseteste and Bacon, and in the preface to the *Perspectiva* he says that visible light is simply an example of the propagation of the power that is the basis of all natural causes. But he disagrees with Grosseteste and Bacon where they say that light rays travel from the observer's eye to the visible object, and instead follows al-Haytham in holding that the rays emanate from the object to interact with the eye.

The *Perspectiva* describes experiments performed by Witelo in his study of refraction. Here his method is similar to that of Ptolemy, where he measures the angle of refraction for light in passing from air into glass and also into water, for angles of incidence ranging from ten to eighty degrees. He tried to explain the results by a number of mathematical generalisations, attempting to relate the differences in refraction to the difference in the densities of the two media. He also produced the colours of the spectrum by passing light through an hexagonal crystal, observing that the blue rays were refracted more than the red.

Witelo also studied refraction in lenses, where he made use of the concept later known as the principle of minimum path. He justified this by the metaphysical notion of economy, saying that ‘It would be futile for anything to take place by longer lines, when it could better and more certainly take place by shorter lines.’

Witelo followed Grossteste in holding that the ‘multiplication of species’ could be used to explain the propagation of any effect, including the divine emanation and astrological influences. In the preface to the *Perspectiva*, which he addresses to William of Moerbeke, he writes ‘of corporeal influences sensible light is the medium’, adding that ‘there is something wonderful in the way in which the influence of divine power flows in to things of the lower world passing through the powers of the higher world.’

The next advances in optics were made by Dietrich of Freiburg (ca. 1250–ca. 1311). Dietrich’s principal work is his treatise *On the Rainbow and Radiant Impressions*, the latter term meaning phenomena produced in the upper atmosphere by radiation from the sun or any other celestial body. He was one of the first to realise that the rainbow is due to the individual drops of rain rather than the cloud as a whole. This led him to make observations with a glass bowl filled with water, which he used as a model raindrop, for he writes ‘that a globe of water can be thought of, not as a diminutive spherical cloud, but as a magnified raindrop’. His observations and geometrical analysis led him to conclude that light is refracted when it enters and leaves each raindrop, and that it is internally reflected once in creating the primary bow and twice for the secondary arc, the second reflection reversing the order of the colours in the spectrum. Although he made a number of errors in his analysis, his theory was far superior to those of any of his predecessors, and it paved the way for researches by his successors.

Dietrich’s theory of the rainbow is very similar to that of his Persian contemporary, Kamal al-Din al-Farisi. In any event, it seems that the emerging European science had by the beginning of the fourteenth century reached a level comparable to that of Arabic scientific research, at least in optics. But whereas the work of al-Farisi was the last great achievement of Arabic optics, Dietrich’s researches would be an important stage in the further development of European studies in the science of light, culminating in the first correct theories of the rainbow and other optical phenomena in the seventeenth century.

The march of Ottoman conquest leading to the fall of Constantinople in 1453 forced a number of Greek scholars to flee from the Byzantine capital to Italy. Basilios Bessarion (ca. 1403–72), a Greek from Trebizond who became a cardinal in the Roman Catholic Church and was nearly elected pope in 1455, had left Constantinople in 1438 and become a cardinal in the Roman Catholic Church, nearly becoming Pope in 1453. Much of Bessarion's energy was spent trying to raise military support in Europe to defend Byzantium against the Turks, but his efforts came to nought, as the Ottomans captured Constantinople in 1453 and then took his native Trebizond in 1461, ending the long history of the Byzantine Empire. Thenceforth Bessarion sought to find support for a crusade against the Turks, but to no avail.

Bessarion devoted much of his time to perpetuating the heritage of Byzantine culture by adding to his collection of ancient Greek manuscripts, which he bequeathed to Venice, where they are still preserved in the Marciana Library. The group of scholars who gathered around Bessarion in Rome included George Trapezuntios, whom he commissioned to translate Ptolemy's *Almagest* from Greek into Latin.

One of Bessarion's diplomatic missions took him in 1460 to Vienna, whose university had become a centre of astronomical and mathematical studies through the work of John of Gmunden (d. 1442), Georg Peurbach (1423–61) and Johannes Regiomontanus (1436–76). John had built astronomical instruments and acquired a large collection of manuscripts, all of which he had bequeathed to the university, thus laying the foundations for the work of Peurbach and Regiomontanus.

Peurbach was an Austrian scholar who had received a bachelor's degree at Vienna in 1448 and a master's in 1453, while in the interim he had travelled in France, Germany, Hungary and Italy. He had served as court astrologer to Ladislaus V, king of Hungary, and then to the king's uncle, the emperor Frederick III. His writings included textbooks on arithmetic, trigonometry and astronomy, his best known works being his *Theoricae novae planetarum* (*New Theories of the Planets*) and his *Tables of Eclipses*.

Regiomontanus, originally known as Johann Muller, took his last name from the Latin for his native Königsberg in Franconia. He studied first at the University of Leipzig from 1447–50, and then at the University of Vienna, where he received his bachelor's degree in 1452, when he was only fifteen, and his master's in 1457. He became Peurbach's associate in a research programme that included a systematic study of the planets as well as observations of astronomical phenomena such as eclipses and comets.

Bessarion was dissatisfied with the translation of Ptolemy's *Almagest* that had been done by George Trapezuntios, and he asked Peurbach and Regiomontanus to write an abridged version. They agreed to do so, for Peurbach had already begun work on a compendium of the *Almagest*, but it was unfinished when he died in April 1461. Regiomontanus completed the compendium about a year later in Italy, where he had gone with Bessarion. He spent part of the next four years in the cardinal's entourage and the rest in his own travels, learning Greek and searching for manuscripts of Ptolemy and other ancient astronomers and mathematicians.

Regiomontanus left Italy in 1467 for Hungary, where he served for four years in the court of King Mathias Corvinus, continuing his researches in astronomy and mathematics. He then spent four years in Nuremberg, where he set up his own observatory and printing press. One of the works that he printed before his premature death in 1476 was Peurbach's *Theoricae novae planetarum*, reprinted in nearly sixty editions up to the seventeenth century. He also published his own *Ephemerides*, the first planetary tables ever printed, giving the positions of the heavenly bodies for every day from 1475 to 1506. Columbus is said to have taken the *Ephemerides* with him on his fourth and last voyage to the New World, and to have used its prediction of the lunar eclipse of 29 February 1504 to frighten the hostile natives of Jamaica into submission.

Regiomontanus' most important mathematical work is his *De triangulis omnimodis*, a systematic method for analysing triangles, which, together with his *Tabulae directionum*, marked what a modern historian of mathematics has called 'the rebirth of trigonometry'.

The astronomical writings of Regiomontanus include the completion of Peurbach's *Epitome of Ptolemy's Almagest*, which he dedicated to Bessarion, a work noted for its emphasis on mathematical methods omitted in other works of elementary astronomy. Copernicus read the *Epitome* when he was a student in Bologna, and at least two propositions in it influenced him in the formulation of his own planetary theory. These propositions seem to have originated with the fifteenth-century Arabic astronomer Ali al-Qushji, and may have been transmitted to Regiomontanus by Bessarion. If so, this would place Bessarion, Regiomontanus and Ali al-Qushji in the long chain that leads, albeit in a convoluted and punctuated way, from Aristarchus of Samos to Copernicus through the Arabic and Latin scholars of the Middle Ages to the dawn of the Renaissance.

CHAPTER 17

Copernicus and his Arabic Predecessors

The development of European science entered a new phase in 1543, when the heliocentric theory of Nicholaus Copernicus (1473–1543) was published, with the planets orbiting around the sun and not the earth.

Copernicus was born on 19 February 1473 at Torun, a town on the Vistula 110 miles north-west of Warsaw. His name was originally Niklas Koppernigk, which he latinised as Nicholaus Copernicus in 1491 when he enrolled at the University of Cracow, where he studied for three or four years without taking a degree. He then went to Italy to study at the universities of Bologna, Padua and Ferrara before returning to spend the rest of his days in what he called ‘this remote corner of the earth’, in what was then Prussia and is now Poland. During the years 1505–12 he lived at Heilsburg Castle, 140 miles north-east of Torun, where his uncle Lucas was bishop. After his uncle died in 1512 he moved to Frauenburg (Frombork), east of Danzig (Gdańsk), where he served as a canon in the cathedral for the rest of his days, making observations of the heavens and developing the mathematical basis of his new astronomical theory.

When Copernicus was at the University of Cracow the astronomer Albert Brudzewski was lecturing there, although there is no record of their having met. Brudzewski had published a commentary on the planetary theory of Peurbach, in which he put forward Ptolemy’s theory that the celestial orbs are not spheres but circles. Brudzewski also used a mathematical method analogous to one employed by the Arabic astronomers Nasir al-Din al-Tusi and ‘Ala’ al-Din ibn al-Shatir, similar to a model that Copernicus would later use in his heliocentric theory.

The textbooks that Copernicus read in his courses at the University of Cracow in mathematics, astronomy and astrology included works by Euclid, Ptolemy, Peurbach and Regiomontanus. The works of a number of Arabic astrologers and philosophers were available in Cracow at that time, including those of Masha'allah, al-Farghani, al-Kindi, Thabit ibn Qurra and Jabir ibn Aflah. Copernicus also bought a number of books in Johann Haller's bookshop in Cracow, including the *Alphonsine Tables* and the *Tabulae directionum* of Regiomontanus, which he had bound together with parts of Peurbach's *Tables of Eclipses* and tables of planetary latitudes.

Around 1512 Copernicus began writing a work entitled *Nicolai Copernici de hypothesibus motuum caelestium a se constitutis commentariolus* (*Nicholas Copernicus, Sketch of his Hypotheses for the Celestial Motions*). This came to be known as the *Commentariolus*, or 'Little Commentary', the first notice of the new astronomical theory that Copernicus had been developing. He gave written copies of this short treatise to a few friends but never published it in book form. Only two manuscript copies have survived, one of which was first published in Vienna in 1878. The earliest record of the *Commentariolus* is a note made in May 1514 by a Cracow professor, Matthias de Miechow, who writes that he had in his library 'a manuscript of six leaves expounding the theory of an author who asserts that the earth moves while the sun stands still'. Matthew was unable to identify the author of this treatise, since Copernicus, with his customary caution, had not written his name on the manuscript. But there is no doubt that the manuscript was by Copernicus, because the author made a marginal note that he reduced all his calculations 'to the meridian of Cracow, because … Frombork … where I made most of my observations … is on this meridian as I infer from lunar and solar eclipses observed at the same time in both places.'

The introduction to the *Commentariolus* discusses the theories of Greek astronomers concerning 'the apparent motion of the planets', noting that the homocentric spheres of Eudoxus were 'unable to account for all the planetary motions', and were supplanted by Ptolemy's 'eccentrics and epicycles, a system which most scholars finally accepted'. But Copernicus took exception to Ptolemy's use of the equant, which led him to think of formulating his own planetary theory, 'in which everything would move uniformly about its proper center, as the rule of absolute motion requires'.

Copernicus goes on to say that after setting out to solve 'this very difficult and almost insoluble problem', he finally arrived at a solution which involved 'fewer and much simpler constructions than were formerly used', provided that he could make certain assumptions, seven in number.

The assumptions are, that there is not a single centre for all the celestial circles, or spheres; that the earth is not the centre of the universe, but only of its own gravity and of the lunar sphere; that the sun is the centre of all the planetary spheres and of the universe; that the earth's radius is negligible compared to its distance from the sun, which in turn is 'imperceptible in comparison to the height of the firmament'; that the apparent diurnal motion of the stellar sphere is due to the rotation of the earth on its axis; that the daily motion of the sun is due to the combined effect of the earth's rotation and its revolution around the sun; and that 'the apparent retrograde and direct motion of the planets arise not from their motion but from the earth's'. He then concludes that 'the motion of the earth alone, therefore, suffices to explain so many inequalities in the heavens'.

Copernicus then goes on to describe the 'Order of the Spheres' in his heliocentric system, in which the time taken by a planetary sphere to make one revolution increases with the radius of its orbit.

> The celestial spheres are arranged in the following order. The highest is the immovable sphere of the fixed stars, which contains and gives position to all things. Beneath it is Saturn, which Jupiter follows, then Mars. Below Mars is the sphere on which we revolve, then Venus; last is Mercury. The lunar sphere revolves around the center of the earth and moves with the earth like an epicycle. In the same order, also, one planet surpasses another in speed of revolution, accordingly as they trace greater or smaller circles. Thus Saturn completes its revolution in thirty years, Jupiter in twelve, Mars in two and one-half, and the earth in one year; Venus in nine months, Mercury in three.

Copernicus used the same system of epicycles that Ptolemy and all of his successors had employed in the geocentric model. He concludes the *Commentariolus* by summarising the number of circles; i.e., deferents, or primary circles, and epicycles, or secondary loops, required to describe all of the celestial motions in his heliocentric system: 'Then Mercury runs on seven circles in all; Venus on five; the earth on three, and round it the moon on four; finally Mars, Jupiter and Saturn on five each. Altogether, therefore, thirty-four circles suffice to explain the entire structure of the universe and the entire ballet of the planets.'

The first indication that the new theories of Copernicus had reached Rome came in the summer of 1533, when the papal secretary Johann Widmanstadt gave a lecture entitled *Copernicana de motuu terra sentential explicani* (*An Explanation of Copernicus' Opinion of the Earth's Motion*) before Pope Clement VI and a group that included two cardinals and a bishop.

After the death of Pope Clement, on 25 September 1534, Widmanstadt entered the service of Cardinal Nicholas Schönberg, who as papal nuncio in Prussia and Poland had undoubtedly heard of Copernicus years before. Schönberg wrote to Copernicus on 1 November 1536, in a letter that may have been drafted by Widmanstadt, urging Copernicus to publish a book on his new cosmology and to send him a copy.

Despite this encouragement Copernicus made no move to publish his researches, but then his attitude changed in the spring of 1539, when he received an unexpected visit from a young German scholar, Georg Joachim van Lauchen, who called himself Rheticus (1514–74). Rheticus, who although only twenty-five was already professor of mathematics at the Protestant University of Wittenberg, explained that he was deeply interested in the new cosmology of Copernicus, who received him hospitably and permitted him to study the manuscript that he had written to explain his theories. During the next ten weeks Rheticus worked with Copernicus in studying the manuscript, which he then summarised in a treatise entitled *Narratio prima* (*First Narrative*), intended as an introduction to the Copernican theory. This was written in the form of a letter from Rheticus to his friend Johann Schöner, under whom he had studied at Wittenberg. The *Narratio prima* was published at Danzig in 1540 with the approval of Copernicus, who is referred to by Rheticus as ‘my teacher’ in the introductory section where he describes the scope of the Copernican cosmology.

Rheticus does not mention the heliocentric theory until after the section on ‘General Considerations Regarding the Motions of the Moon, Together with the New Lunar Hypotheses.’ There he says that the new model explains the retrograde motion of the planets ‘by having the sun occupy the center of the universe, while the earth revolves instead of the sun on the eccentric’.

The *Narratio prima* proved to be so popular that a second edition was published at Basel the following year. But Copernicus still hesitated to publish his manuscript, which he sent for safekeeping to his old friend Tiedemann Giese, Bishop of Culm. Finally, in the autumn of 1541, Giese received permission from Copernicus to send his manuscript to Rheticus, who was to take it to the press of Johannes Petreius in Nuremberg for publication. The title chosen for the book was *De Revolutionibus Orbium Coelestium Libri VI* (*Six Books Concerning the Revolutions of the Heavenly Spheres*). The title stems from the fact that Copernicus believed the celestial bodies to be embedded in the same crystalline spheres, or rather spherical shells, as those first proposed by Aristotle, though he had them revolving around the sun rather than the earth.

Toward the end of the following year Copernicus suffered a series of strokes that left him half-paralysed, and it was obvious to his friends that his end was near. Meanwhile Rheticus had taken a leave of absence from the University of Wittenberg in May 1542 to supervise the printing of *De Revolutionibus* in Nuremberg. Five months later he left Nuremberg to take up a post at the University of Leipzig, leaving responsibility for the book in the hands of Andreas Osiander, a local Lutheran clergyman. Osiander took it upon himself to add an anonymous introduction entitled *Ad lectorem* (*To the Reader*), which was to be the cause of considerable controversy regarding the Copernican theory.

De Revolutionibus finally came off the press in the spring of 1543. The first printed copy was sent to Copernicus, and according to tradition it reached him a few hours before he died, on 24 May 1543. Tiedemann Giese describes the last days of Copernicus in a letter to Rheticus: 'He had lost his memory and mental vigor many days before; and he saw his completed work only at his last breath upon the day that he died.'

The introduction to *De Revolutionibus*, the *Ad lectorum* written by Osiander, is entitled 'To the Reader Concerning the Hypotheses of this Work.' This says that the book is designed as a mathematical device for calculation and not as a real description of nature. The *Ad lectorum* was intended to deflect criticism of the heliocentric cosmology by those who thought that it contradicted the Bible, particularly the passage in the *Book of Joshua* that says 'The sun stood still in the middle of the sky and delayed its setting for almost a whole day.' Martin Luther, referring to the Copernican theory, had already been quoted as saying that 'People give ear to an upstart astrologer who strove to show that the earth revolves, not the heavens, or the firmament, the sun and the moon. This fool wishes to reverse the entire science of astronomy, but sacred Scripture tells us that Joshua commanded the Sun to stand still and not the Earth.' Copernicus himself had been worried about such criticism, as evidenced by his statement in the Preface of *De Revolutionibus*, which he dedicated to Pope Paul III: 'I can reckon easily enough, Most Holy Father, that as soon as certain people learn that in these books of mine which I have written about the revolutions of the spheres of the world I attribute certain motions to the terrestrial globe they will immediately shout to have me and my opinion hooted off the stage.'

The first eight chapters of Book I of *De Revolutionibus* give a greatly simplified description of the Copernican cosmology and its philosophical basis. Copernicus begins with arguments for the spherical nature of the universe; the sphericity of the earth, moon, sun and planets; and the uniform circular motion of the planets around the sun. He shows how the rotation of the earth on its axis, together with its revolution about the sun, can easily explain the observed motions of the celestial bodies. The absence of stellar parallax he explains by the fact that the radius of the earth's orbit is negligible compared to the distance of the fixed stars.

Chapter 9 is entitled 'Whether many movements can be attributed to the Earth, and concerning the center of the world.' Here Copernicus abandons the Aristotelian doctrine that the earth is the sole source of gravity, and instead takes the first step toward the Newtonian theory of universal gravitation, writing that 'I myself think that gravity or heaviness is nothing except a certain natural appetency implanted in the parts by the divine providence of the universal Artisan, in order that they should unite with one another in their oneness and wholeness and come together in the form of a globe.'

Chapter 10 is entitled 'On the order of the celestial orbital circles.' Here Copernicus removes the ambiguity concerning Mercury and Venus, which in the Ptolemaic model were sometimes placed 'above' the sun and sometimes 'below'. The Copernican system has Mercury as the closest planet to the sun, followed by Venus, Earth, Mars, Jupiter and Saturn, surrounded by the sphere of the fixed stars, and with the moon orbiting the earth. This model is simpler and more harmonious than Ptolemy's, for all of the planets revolve in the same sense, with velocities decreasing with their distance from the sun, which, as Copernicus writes, sits enthroned at the centre of the cosmos.

> In the center of all the celestial bodies rests the Sun. For who would place this lamp of a very beautiful temple in another or better place than this where from it can illuminate everything at the same time. As a matter of fact, not unhappily do some call it the lantern, others the mind and still others, the pilot of the world…And so the sun, as if resting on a kingly throne, governs the family of stars which wheel around.

Chapter 11 is 'A Demonstration of the Threefold Movement of the Earth,' while the remaining three chapters of Book One are concerned with the application of plane and spherical geometry and trigonometry to problems in astronomy. The three motions to which Copernicus refers are the earth's rotation on its axis, its revolution around the sun, and a third conical motion, which he introduced to keep the earth's axis pointing in the same direction while the crystalline sphere in which it was embedded rotated annually. The period of this supposed third motion he took to be slightly different than the time it takes the earth to rotate around the sun, the difference being due to the very slow precession of the equinoxes.

Book Two is a detailed introduction to astronomy and spherical trigonometry, together with mathematical tables and a catalogue of the celestial coordinates of 1,024 stars, most of them derived from Ptolemy, adjusted for the precession of the equinoxes.

Book Three is concerned with the precession of the equinoxes and the movement of the earth around the sun. Here the theory is unnecessarily complicated, since Copernicus, besides combining precession with his ‘third motion’ of the earth, inherited two effects from his predecessors, one of them spurious. The first effect was the mistaken notion, stemming from the trepidation theory, that the precession was not constant but variable, and the other was the variation in the inclination of the ecliptic.

Book Four deals with the motion of the moon around the earth; Books Five and Six study the motions of the planets. Here, as with the motions of the sun, Copernicus used eccentrics and epicycles just as Ptolemy had done, though his conviction that the celestial motions were combinations of circular motion at constant angular velocity made him refrain from using the Ptolemaic device of the equant. Because of the complexity of the celestial motions, Copernicus was forced to use about as many circles as had Ptolemy, and so there was little to choose from between the two theories so far as economy was concerned, and both were capable of giving results of comparable accuracy. The advantages of the Copernican system were that it was more harmonious; it removed the ambiguity about the order of the inner planets; it explained the retrograde motion of the planets as well as their variation in brightness; and it allowed both the order and relative sizes of the planetary orbits to be determined from observation without any additional assumptions.

Copernicus refers to Aristarchus of Samos thrice in *De Revolutionibus*, twice regarding his predecessor’s measurement of the inclination of the ecliptic and once concerning his measurement of the length of the solar year. But nowhere does he mention that Aristarchus had in the mid-third century BC proposed that the sun and not the earth was the centre of the cosmos. Copernicus had referred to the heliocentric theory of Aristarchus in his original manuscript, but deleted it from the edition of *De Revolutionibus* printed in 1543.

Copernicus is known to have possessed a copy of George Valla’s *Outline of Knowledge*, printed by Aldus Manutius at Venice in 1501, which included a translation of a work of Aetius (Pseudo-Plutarch) containing two references to Aristarchus. One has Aristarchus ‘assuming that the heavens are at rest while the earth revolves along the ecliptic, simultaneously rotating about its own axis’; the other says that in his theory the earth ‘spins and turns, which Seleucus afterwards advanced as an established opinion’.

Copernicus was almost certainly familiar with Archimedes' *Sand-Reckoner*, which contains the earliest reference to the heliocentric theory of Aristarchus. There Archimedes says that Aristarchus explains the lack of stellar parallax in his heliocentric theory by supposing that the radius of the earth's move around the sun is negligible compared to the distance of the stars. This is essentially the same explanation given by Copernicus in his *Commentariolus*, where in the fourth of his assumptions he states that 'the distance from the earth to the sun is imperceptible in comparison to the height of the firmament'. Copernicus uses this same argument in *De Revolutionibus*, where at the end of Book One, chapter 10 he contrasts the retrograde motion of the planets with the unchanging array of the stars, noting that 'How exceedingly fine is the godlike work of the Best and Greatest Artist!'

Thus it is possible that Copernicus was aware of the heliocentric theory of Aristarchus and that he chose to suppress mention of it in *De Revolutionibus*, perhaps so as not to lessen the importance of his own life's work, setting the celestial orbs in motion around the sun rather than the earth.

Copernicus mentions some of the Arabic astronomers whose observations and theories he used in *De Revolutionibus*, namely al-Battani, al-Bitruji, al-Zarqallu, Ibn Rushd (Averroës) and Thabit ibn Qurra. He also mentions al-Battani in his *Commentariolus.* But he does not mention Nasir al-Din al-Tusi, Mu'ayyad al-Din al'-Urdi, Qutb al-Din al-Shirazi and Ala' al-Din ibn al-Shatir. F. Jamil Ragep describes the advances made by these Arabic astronomers in the thirteenth and fourteenth centuries:

> In essence, these astronomers developed mathematical tools (such as the 'Tusi couple' and the 'Urdi lemma') that allowed connected circular motions to reproduce approximately the effects brought about by devices such as Ptolemy's equant ... What this allowed Tusi and his successors to do was to isolate the aspect of Ptolemy's equant model that brought about a variation in distance between the epicycle center and the earth's center from the aspect that resulted in a variation in speed of the epicycle center about the Earth. Such mathematical dexterity allowed these astronomers to present models that to a great extent restored uniform circular motion to the heavens while at the same time producing motions of the planets that were almost equivalent to those of Ptolemy.

Ragep goes on to quote from an article by Noel Swerdlow and Otto Neugebauer, which indicates that some of the mathematical methods used by Copernicus were based on those of Arabic, Iranian and Turkic astronomers.

> The planetary models for longitude in the *Commentariolus* are all based upon the models of Ibn al-Shatir – although the arrangements for the inferior planets is incorrect – while those for the superior planets in *De Revolutionibus* use the same arrangement as ‘Urdi’s and Shirazi’s model, and for the interior planets the smaller epicycle is converted into an equivalent rotating eccentricity that constitutes a correct interpretation of Ibn al-Shatir’s model. In both the *Commentariolus* and *De revolutionibus* the lunar model is identical to Ibn al-Shatir’s and finally in both works Copernicus makes it clear that he was addressing the same physical problems as his predecessors. It is obvious that with regard to these problems, his solutions were the same.

Ragep then quotes Swerdlow on the question of how Copernicus might have acquired the theories of these Arabic astronomers, where he says ‘How Copernicus learned of the models of his [Arabic] predecessors is not known – a transmission through Italy is the most likely path – but the relation between the models is so close that independent invention by Copernicus is all but impossible.’

> All that someone like Copernicus had to do was take any of Ibn al-Shatir’s models, hold the sun fixed and then allow the Earth’s sphere, together with all the other planetary spheres that were centered on it, to revolve around the sun instead ... that was the very step taken by Copernicus when he seems to have adopted the same geocentric models as those of Ibn al-Shatir and then translated them to heliocentric ones whenever the situation called for it.

Thus the Copernican theory seems to have been based on mathematical models that he acquired from his Arabic predecessors, though he took the revolutionary step of putting the sun at the centre of the planetary orbits rather than the earth.

CHAPTER 18

The Scientific Revolution

The Copernican theory opened the way for an intellectual upheaval that came to be known as the Scientific Revolution, whose principal figures were Tycho Brahe (1546–1601), Johannes Kepler (1571–1630), Galileo Galilei (1564–1642) and Isaac Newton (1642–1727), though physicians, alchemists, botanists, philologists and historians all played important roles. Without all of these players, the shift would not have been so far-reaching and so deep.

The heliocentric theory of Copernicus had very few believers at first, though it gained some support when it was used as the basis for new, though not necessarily better, astronomical tables. The first of these were the *Prutenic Tables*, published in 1541 by Erasmus Reinhold (1511–53), who in the introduction praises Copernicus but is silent about his heliocentric theory.

The *Prutenic Tables* were the first complete planetary tables prepared in Europe for three centuries. They were demonstrably superior to the older tables, which were now out of date, and so they were used by most astronomers, lending legitimacy to the Copernican theory even when those who used them did not acknowledge the sun-centred cosmology of Copernicus. As the English astronomer Thomas Blundeville wrote in the preface to an astronomy text in 1594: 'Copernicus … affirmeth that the earth turneth about and that the sun standeth still in the midst of the heavens, by help of which false supposition he hath made truer demonstrations of the motions and revolutions of the celestial spheres, than ever were made before.'

Meanwhile astronomy was being revolutionised by the Danish astronomer Tycho Brahe, who in the last quarter of the seventeenth century made systematic observations of significantly greater accuracy than any ever done in the past, all just before the invention of the telescope.

Tycho made his first important observation in August 1563, when he noted a conjunction of Saturn and Jupiter. He found that the *Alfonsine Tables* were a month off in predicting the date of the conjunction, and that the *Prutenic Tables* were several days in error. This convinced Tycho that new tables were needed, and that they should be based upon more accurate, precise and systematic observations, which he would make with instruments of his own design in his own observatory.

The first of Tycho's observatories was at Augsburg in Germany, where he lived in the years 1569–71. The instruments that he designed and built for his observatory included a great quadrant with a radius of some 19 feet for measuring the altitude of celestial bodies. He also constructed a huge sextant with a radius of 14 feet for measuring angular separations, as well as a celestial globe 10 feet in diameter on which to mark the positions of the stars in the celestial map that he began to create.

Tycho returned to Denmark in 1571, and on 11 November of the following year he began observing a nova, or new star, that suddenly appeared in the constellation Cassiopeia, exceeding even the planet Venus in its brilliance.

Tycho's measurements indicated that the nova was well beyond the sphere of Saturn, and the fact that its position did not change showed that it was not a comet. This was clear evidence of a change taking place in the celestial region, where, according to Aristotle's doctrine, everything was perfect and immutable.

The nova eventually began to fade, its colour changing from white to yellow and then red, finally disappearing from view in March 1574. By then Tycho had written a brief tract entitled *De nova stella* (*The New Star*), which was published at Copenhagen in May 1573. The treatise impressed King Frederick II of Denmark, who gave Tycho an annuity along with the small offshore island of Hveen, in the Oresund Strait north of Copenhagen, the revenues of which would enable him to build and equip an observatory. Tycho settled on Hveen in 1576, calling the observatory Uraniborg, meaning 'City of the Heavens'. That same year Tycho and his assistants began a series of observations of unprecedented accuracy and precision that would continue for the next two decades, laying the foundations for what would prove to be the new astronomy.

A spectacular comet appeared in 1577 and Tycho made detailed observations that led him to conclude that it was farther away than the moon, in fact even beyond the sphere of Mercury, and that it was in move around the sun among the outer planets. This contradicted the Aristotelian doctrine that comets were meteorological phenomena occurring below the sphere of the moon. He was thus led to reject Aristotle's concept of the homocentric crystalline spheres, and he concluded that the planets were moving independently through space.

Despite his admiration for Copernicus, Tycho rejected the heliocentric theory, both on physical grounds and on the absence of stellar parallax. Faced with the growing debate between the Copernican and Ptolemaic theories, Tycho was led to propose his own planetary model, with Mercury and Venus revolving around the sun, which together with the other planets and the moon orbited around the stationary earth. Tycho believed that his model combined the best features of both the Ptolemaic and Copernican theories, since it kept the earth stationary and explained why Mercury and Venus were never very far from the sun.

Tycho's patron Frederick II died in 1588 and was succeeded by his son Christian IV, who was then eleven years old. When Christian came of age, in 1596, he informed Tycho that he would no longer support his astronomical research. Tycho was thus forced to abandon Uraniborg, taking with him all of his astronomical instruments and records, hoping to find a new royal patron.

Tycho moved first to Copenhagen and then in turn to Rostock and Wandsburg Castle, outside Hamburg. He remained for two years at Wandsburg Castle, where in 1598 he published his *Astronomiae instauratae mechanica*, a description of all his astronomical instruments. He sent copies of his treatise to all of the wealthy and powerful people who might be interested in supporting his further researches. He appending his star catalogue to the copy he presented to the Emperor Rudolph II, who agreed to support Tycho's work, appointing him as the court astronomer.

Thus in 1600 Tycho moved to Prague, where he set up his instruments and created a new observatory at Benatky Castle, several miles north-east of the city. Soon afterwards he hired the young German mathematician Johannes Kepler, who had sent him an interesting treatise on astronomy, the *Mysterium Cosmographicum*, based on the Copernican theory. In the introduction to this book Kepler writes of his excitement on discovering the work of Copernicus, which he described as 'a still unexhausted treasure of truly divine insight into the magnificent order of the whole world and of all bodies'.

Kepler sent copies of his treatise to a number of scientists, including Galileo. In his letter of acknowledgement, dated 4 August 1597, Galileo congratulated Kepler for having had the courage, which he himself lacked, of publishing a work supporting the Copernican theory.

Kepler wrote back to Galileo on 13 October 1597, encouraging him to continue supporting the Copernican theory. ‘Have faith, Galilii, and come forward!’ he wrote. ‘If my guess is right, there are but few of the prominent mathematicians of Europe who would wish to secede from us: such is the power of truth.’

Kepler finally arrived in Prague with his family early in 1600, beginning a brief but extraordinarily fruitful collaboration with Tycho. When Kepler began work at Prague he had hopes that he could take Tycho’s data and use it directly to check his own planetary theory. But he was disappointed to find that most of Tycho’s data was still in the form of raw observations, which first had to be subjected to mathematical analysis. Moreover Tycho was extremely possessive of his data and would not reveal any more of it than Kepler needed for his work.

Tycho assigned Kepler the task of analysing the orbit of Mars, which up to that time had been the responsibility of his assistant Longomontanus, who had just resigned. Mars and Mercury are the only visible planets with eccentricities large enough to make their orbits significantly different from perfect circles. But Mercury is so close to the sun that it is difficult to observe, leaving Mars as the ideal planet for checking a mathematical theory, which is why Kepler was so enthusiastic at being able to analyse its orbit.

Early in the autumn of 1601 Tycho brought Kepler to the imperial court and introduced him to Emperor Rudolph. Tycho then proposed to the emperor that he and Kepler compile a new set of astronomical tabulations to be called the *Rudolfine Tables*, which Rudolph agreed to subsidise.

Soon afterwards Tycho fell ill, and after suffering in agony for eleven days he died on 24 October 1601. On his deathbed he made Kepler promise that the *Rudolfine Tables* would be completed, and he expressed his hopes that it would be based on the Tychonic planetary model. As Kepler later wrote of Tycho’s final conversation with him: ‘although he knew I was of the Copernican persuasion, he asked me to present all my demonstrations in conformity with his hypothesis.’

Two days after Tycho’s death Emperor Rudolph appointed Kepler as court mathematician and head of the observatory in Prague. Kepler thereupon resumed his work on Mars, now with unrestricted access to all of Tycho’s data. At first he tried the traditional Ptolemaic methods – epicycle, eccentric and equant – but no matter how he varied the parameters the calculated positions of the planet disagreed with Tycho’s observations by up to eight minutes of arc. His faith in the accuracy of Tycho’s data led him to conclude that the Ptolemaic theory of epicycles, which had been used by Copernicus, would have to be replaced by a completely new theory.

After eight years of intense effort Kepler was finally led to what are now known as his first two laws of planetary motion. The first law is that the planets travel in elliptical orbits, with the sun at one of the two focal points of the ellipse. The second law states that a radius vector drawn from the sun to a planet sweeps out equal areas in equal times, so that when the planet is close to the sun it moves rapidly and when far away it goes slowly. These two laws, which appeared in Kepler's *Astronomia nova* (*The New Astronomy*), published in 1609, became the basis for his subsequent work on the *Rudolfine Tables*. Kepler's first two laws of planetary motion eliminated the need for the epicycles, eccentrics and deferents that had been used by astronomers from Ptolemy to Copernicus.

Meanwhile the whole science of astronomy had been profoundly changed by the invention of the telescope. The earliest telescope seems to have appeared in 1604, when a Dutch optician named Zacharias Janssen constructed one from a specimen belonging to an unknown Italian, after which he sold some of them at fairs in northern Europe. After hearing of the telescope, Galileo constructed one in his workshop in 1609, after which he offered it to the Doge of Venice for use in war and navigation. After improving on his original design, he began using his telescope to observe the heavens, and in March 1610 he published his discoveries in a little book called *Siderius nuncius* (*The Starry Messenger*).

The book begins with his observations of the moon, which he found to look very much like the earth, with mountains, valleys and what he thought were seas. Seen in the telescope, the planets were pale illuminated discs, whereas the stars remained brilliant points of light. The Milky Way proved to consist of numerous stars, not a nebula reflecting the light of the sun, as some had thought, nor an atmospheric phenomenon, as Aristotle had concluded. He counted more than ninety stars in Orion's belt, where only nine are visible to the naked eye. He discovered four moons orbiting around Jupiter, a solar system in miniature, which he used as an additional argument in favour of the Copernican theory. He called the Jovian moons the 'Medicean Stars' in honour of Cosimo de Medici, the Grand Duke of Tuscany. Cosimo responded by making Galileo his court philosopher and appointing him to the chair of mathematics at the University of Pisa. Galileo had no obligation to teach at the University of Pisa or even to reside in the city, and so after his appointment, in September 1610, he departed to take up residence in Florence.

Galileo sent a copy of the *Siderius nuncius* to Kepler, who received it on 8 April 1610. During the next eleven days Kepler composed his response in a little work called *Dissertatio cum Nuncio sidereal* (*Answer to the Sidereal Messenger*), in which he expressed his enthusiastic approval of Galileo's discoveries and reminded readers of his own work on optical astronomy, as well as speculating on the possibility of inhabitants on the moon and arguing against an infinite universe.

Kepler borrowed a telescope from the Elector Ernest of Cologne at the end of August 1610, and for the next ten days he used it to observe the heavens, particularly Jupiter and its moons. His excitement over the possibilities of the new instrument was such that he spent the next two months making an exhaustive study of the passage of light through lenses, which he published later in 1610 under the title *Dioptrice*, which became one of the foundation stones of the new science of optics.

The death of Rudolph II early 1612 forced Kepler to leave Prague and take up the post of district mathematician at Linz, where he remained for the next fourteen years. One of his official duties was a study of chronology, part of a programme of calendar reform instituted by the Archduke Ferdinand II, son of the late emperor Rudolph.

During the period that Kepler lived in Linz he continued his calculations on the *Rudolfine Tables* and published two other major works, the first of which was the *Harmonice Mundi* (*Harmony of the World*), which appeared in 1619. The most important part of the *Harmonice Mundi* is the relationship now known as Kepler's Third Law of Planetary Motion, which he discovered on 15 May 1618, and presents in Book V. The law states that for each of the planets the square of the period of its orbital motion is proportional to the cube of its distance from the sun (or, strictly speaking, the semi-major axis of its elliptical orbit).

There had been speculations about the relation between the periods of planetary orbits and their radii since the times of Pythagoras, Plato and Aristotle, and Kepler was very excited that he had at last, following in the footsteps of Ptolemy, found the mathematical law 'necessary for the contemplation of celestial harmonies'.

In 1626 Kepler was forced to leave Linz and move to Ulm, where he published the *Rudolfine Tables* in September 1627, dedicating them to the Archduke Ferdinand II. The new tables were far more accurate than any in the past, and they remained in use for more than a century. Kepler used his tables to predict that Mercury and Venus would make transits across the disk of the sun in 1631.

The transit of Venus was not observed in Europe because it took place at night. The transit of Mercury was observed by Pierre Gassendi in Paris on 7 November 1631, representing a triumph for Kepler's astronomy, for his prediction was in error by only 10 minutes of arc as compared to 5 degrees for tables based on Ptolemy's model. But Kepler did not live to see his theories vindicated, for he passed away on 15 November 1630.

Meanwhile Galileo had been active in advancing the cause of Copernicanism against the accepted cosmology of Aristotle, which in its reinterpretation by St Thomas Aquinas formed part of the philosophical basis for Roman Catholic theology. At the beginning of March 1616 the Holy Office of the Inquisition in Rome placed the works of Copernicus and all other writings that supported it on the Index, the list of books that Catholics were forbidden to read, including those of Kepler. The decree held that believing the sun to be the immovable centre of the world is 'foolish and absurd, philosophically false and formally heretical'. Pope Paul V instructed Cardinal Bellarmine to censure Galileo, admonishing him not to hold or defend Copernican doctrines any longer. On 3 March Bellarmine reported that Galileo had acquiesced to the Pope's warning, and that ended the matter for the time being.

After his censure Galileo returned to his villa at Arcetri outside Florence, where for the next seven years he remained silent. But then in 1623, after the death of Paul V, Galileo took hope when he learned that his friend Maffeo Cardinal Barbarini had succeeded as Pope Urban VIII. Heartened by his friend's election, Galileo immediately proceeded to publish a treatise entitled *Il Saggiatore* (*The Assayer*), which appeared later that year, dedicated to Urban VIII.

Il Saggiatore was favourably received in the Vatican, and Galileo went to Rome in the spring of 1623 and had six audiences with the Pope. Urban praised the book, but he refused to rescind the 1616 edict against the Copernican theory, though he said that if it had been up to him the ban would not have been imposed. Galileo did receive Urban's permission to discuss Copernicanism in a book, but only if the Aristotelian-Ptolemaic model was given equal and impartial attention.

Encouraged by his conversations with Urban, Galileo spent the next six years writing a book called the *Dialogue Concerning the Chief World Systems, Ptolemaic and Copernican*, which was completed in 1630 and finally published in February 1632. The book is divided into four days of conversations between three friends: Salviati the Copernican, Sagredo the intelligent sceptic who had been converted to Copernicanism, and Simplicio the Aristotelian.

The arguments for Copernicanism were very persuasive and poor Simplicio, the Aristotelian, is defeated at every turn. Simplicio's closing remark represents Galileo's attempt to reserve judgment in the debate, where he says that 'it would still be excessive boldness for anyone to limit and restrict the Divine power and wisdom to some particular fancy of his own'. This statement apparently was almost a direct quote of what Pope Urban had said to Galileo in 1623. When Urban read the *Dialogue* he remembered these words and was deeply offended, feeling that Galileo had made a fool of him and taken advantage of their friendship to violate the 1616 edict against teaching Copernicanism. The Florentine ambassador Francesco Niccolini reported that after discussing the *Dialogue* with Urban, the Pope broke out in great anger and fairly shouted, 'Your Galileo has ventured to meddle with things that he ought not, and with the most grave and dangerous subjects that can be stirred up these days.'

Urban directed the Holy Office to consider the affair and summoned Galileo to Rome. Galileo arrived in Rome in February 1633, but his trial before the court of the Inquisition did not begin until April. There he was accused of having ignored the 1616 edict of the Holy Office not to teach Copernicanism. The court deliberated until June before giving its verdict, and in the interim Galileo was confined in the palace of the Florentine ambassador. He was then brought once again to the Holy Office, where he was persuaded to acknowledge that he had gone too far in his support of the Copernican 'heresy', which he now abjured. He was thereupon sentenced to indefinite imprisonment and his *Dialogue* placed on the *Index*. The sentence of imprisonment was immediately commuted to allow him to be confined in one of the Roman residences of the Medici family, after which he was moved to Siena and then, in April 1634, allowed to return to his villa at Arcetri.

After he returned home Galileo took up again the researches he had abandoned a quarter of a century earlier, principally the study of motion. This gave rise to the last and greatest of his works, *Discourses and Mechanical Demonstrations Concerning Two New Sciences, of Mechanics and of Motions,* completed in 1636, when Galileo was seventy-two and suffering from failing eyesight. Since publication in Italy was out of the question because of the papal ban on Galileo's works, his manuscript was smuggled to Leyden, where the *Discourses* was published in 1638, by which time he was completely blind.

Galileo died at Arcetri on 8 January 1642, thirty-eight days before what would have been his seventy-eighth birthday. The Grand Duke of Tuscany sought to erect a monument in his memory, but he was advised not to do so for fear of giving offence to the Holy Office, since the Pope had said that Galileo 'had altogether given rise to the greatest scandal throughout Christendom'.

The Scientific Revolution climaxed with the work of Newton, who was born on 25 December 1642, the same year that Galileo had died. His humble background delayed his formal education, but he was finally admitted to Cambridge, where he was enrolled at Trinity College in June 1661. At Cambridge Newton was introduced to both Aristotelian science and cosmology as well as the new physics, astronomy and mathematics that had been developed in western Europe. In 1663 he began studying under Isaac Barrow (1630–77), the newly-appointed Lucasian professor of mathematics and natural philosophy. Barrow edited the works of Euclid, Archimedes and Apollonius, and published his own works on geometry and optics, with the assistance of Newton.

By Newton's own testimony he began his researches in mathematics and physics late in 1664, shortly before an outbreak of plague closed the university at Cambridge and forced him to return home. During the next two years, his *anni mirabilis*, he says that he discovered his laws of universal gravitation and motion as well as the concepts of centripetal force and acceleration. He applied these laws to compute the centripetal acceleration at the earth's surface caused by its diurnal rotation, finding that it was less than the acceleration due to gravity by a factor of 250, thus settling the old question of why objects are not flung off the planet by its rotation. He computed the centripetal force necessary to keep the moon in orbit, comparing it to the acceleration due to gravity at the earth's surface, and found that they were inversely proportional to the squares of their distances from the centre of the earth. Then, using Kepler's third law of planetary motion together with the law of centripetal acceleration, he verified the inverse square law of gravitation for the solar system. At the same time he laid the foundations for the calculus and formulated his theory for the dispersion of white light into its component colours. 'All this was in the two plague years 1665 and 1666,' he wrote, 'for in those years I was in the prime of my age for invention & minded Mathematicks & Philosophy more than at any time since.'

When the plague subsided Newton returned to Cambridge in the spring of 1667. Two years later he succeeded Barrow as Lucasian professor of mathematics and natural philosophy, a position he was to hold for nearly thirty years.

During the first few years after he took up his professorship Newton devoted much of his time to research in optics and mathematics. He continued his experiments on light, examining its refraction in prisms and thin glass plates as well as working out the details of his theory of colours. He also carried on with his chemical experiments, where, like many of his contemporaries, he was still influenced by the old notions of alchemy.

Newton's silence allowed Robert Hooke to claim that he was the first to discover the inverse square law of gravitational force. In November

1662 Hooke had been appointed as the first Curator of Experiments at the newly-founded Royal Society in London, a position he held until his death in 1704, making many important discoveries in mechanics, optics, astronomy, technology, chemistry and geology.

Meanwhile Newton continued his researches on light, and he succeeded in making a reflecting telescope that was a significant improvement on any of the refractors then in use. News of his invention leaked out and he was urged to exhibit it at the Royal Society in London, which was just then beginning to hold its formal weekly meetings. The exhibit was so successful that Newton was proposed for membership in the Royal Society, and on 11 January 1672 he was elected as a Fellow.

As part of his obligations as a Fellow, Newton wrote a paper on his optical experiments, which he submitted on 28 February 1672, to be read at a meeting of the Society. The paper, subsequently published in the *Philosophical Transactions of the Royal Society*, described his discovery that sunlight is composed of a continuous spectrum of colours, which can be dispersed by passing light through a refracting medium such as a glass prism. He found that the 'rays which make blue are refracted more than the red', and he concluded that sunlight is a mixture of light rays, some of which are refracted more than others. Furthermore, once sunlight is dispersed into its component colours it cannot be further decomposed. This meant that the colours seen on refraction are inherent in the light itself and are not imparted to it by the refracting medium.

The paper was widely criticised by some of Newton's contemporaries, it did not confirm or deny any general philosophy of nature, while others insisted that his experimental findings were false, since they themselves could not find the phenomena that he had reported. Newton replied patiently to each of these criticisms in turn, but after a time he began to regret ever having presented his work in public. To make matters worse, Hooke began to claim that Newton's telescope was far inferior to one that he himself had made.

For these and other reasons Newton, early in 1673, offered his resignation to the Royal Society. The Secretary, Henry Oldenburg, refused to accept his resignation and persuaded him to remain. Then in 1676, after a public attack by Hooke, Newton broke off almost all association with the Royal Society. That same year Hooke became Secretary of the Society and wrote a conciliatory letter in which he expressed his admiration for Newton. Referring to Newton's theory of colours, Hooke said that he was 'extremely well pleased to see those notions promoted and improved which I long since began, but had not time to compleat'.

Newton replied in an equally conciliatory tone, referring to Descartes' work on optics. 'What Descartes did was a good step. You have added much several ways, and especially in taking the colours of thin plates into philosophical consideration. If I have seen further than Descartes, it is by standing on the shoulders of Giants.'

But despite these friendly sentiments, the two were never completely reconciled, and Newton maintained his silence. Nevertheless they continued to communicate with one another, a correspondence that was to lead again and again to controversy, the bitterest dispute arising from Hooke's claim that he had discovered the inverse square law of gravitation before Newton.

By 1684 others besides Hooke and Newton were convinced that the gravitational force was responsible for holding the planets in their orbits, and that this force varied with the inverse square of their distance from the sun. Among them were the astronomer Edmund Halley (1656–1742), a good friend of Newton's and a fellow-member of the Royal Society. Halley made a special trip to Cambridge in August 1684 to ask Newton 'what he thought the Curve would be that would be described by the Planets supposing the force of attraction toward the Sun to be reciprocal to the square of their distance from it'. Newton replied immediately that it would be an ellipse, but he could not find the calculation, which he had done seven or eight years before. And so he was forced to rework the problem, after which he sent the solution to Halley that November.

By then Newton's interest in the problem had revived, and he developed enough material to give a course of nine lectures in the autumn term at Cambridge, under the title of *De Motu Corporum* (*The Motion of Bodies*). When Halley read the manuscript of *De Motu* he realised its immense importance, and he obtained Newton's promise to send it to the Royal Society for publication. Newton began preparing the manuscript for publication in December 1684, and sent the first book of the work to the Royal Society on 28 April 1686.

On 22 May Halley wrote to Newton saying that the Society had entrusted him with the responsibility for having the manuscript printed. But he added that Hooke, having read the manuscript, claimed that it was he who had discovered the inverse square nature of the gravitational force and thought that Newton should acknowledge this in the preface. Newton was very much disturbed by this, and in his reply to Halley he went to great lengths to show that he had discovered the inverse square law of gravitation and that Hooke had not contributed anything of consequence.

The first edition of Newton's work was published in midsummer 1687 at the expense of Halley, since the Royal Society had found itself financially unable to fund it. Newton entitled his work *Philosophicae Naturalis Principia Mathematica* (*The Mathematical Principles of Natural Philosophy*), referred to more simply as the *Principia.* In the introductory section of the *Principia* Newton states his three laws of motion and his law of universal gravitation:

> Law 1: Every body perseveres in its state of being at rest, or of moving uniformly forward, except insofar as it is compelled to change its state of motion by forces impressed … Law 2: A change of motion is proportional to the motive force impressed and takes place along the straight line in which that force is impressed … Law 3: To every action there is always an opposite and equal reaction; in other words, the action of two bodies upon each other are always equal, and always opposite in direction.

Then in Book I he analyses both terrestrial and celestial motion to establish his law of universal gravitation, which states that the gravitational force between any two bodies in the universe depends on the product of their masses and the inverse square of the distance between them. The rest of the *Principia* is a systematic application of the law of gravitation and the three laws of motion to explain phenomena ranging from the tides and the motion of projectiles and those of the celestial bodies to the precession of the equinoxes, a synthesis of the new physics and astronomy.

A second edition of the *Principia* was published in 1713 and a third in 1726, in both cases with a preface written by Newton. Meanwhile Newton had in 1704 published his researches on light, much of which had been done early in his career. Unlike the *Principia*, which was in Latin, the first edition of his new work was in English, entitled *Opticks, or a Treatise of the Reflexions, Refractions, Inflexions and Colours of Light.* The first Latin edition appeared in 1706, and subsequent English editions appeared in 1717, 1721 and 1730; the last, which came out three years after Newton's death, bore a note stating that it was 'corrected by the author's own hand, and left before his death, with his bookseller'.

In the introduction to the *Opticks* Newton reveals the purpose he had in mind when composing his work. 'My design in this Book,' he writes, 'is not to explain the Properties of Light by Hypotheses, but to propose and prove them by Reason and Experiment.'

The topics dealt with in Book I include the laws of reflection and refraction, the formation of images, and the dispersion of light into its component colours by a glass prism. Other topics include the properties of lenses and Newton's reflecting telescope; the optics of human vision; the theory of the rainbow; and an exhaustive study of colour. Newton's proof of the law of refraction is based on the erroneous notion that light travels more rapidly in glass than in air, an error stemming from his that light was corpuscular in nature.

Newton's corpuscular view of light came from his acceptance of the atomic theory. He writes of his admiration for 'the oldest and most celebrated Philosophers of Greece ... who made a Vacuum, and Atoms, and the Gravity of Atoms, the first Principles of their Philosophy'. But in Book II, in the section entitled 'Observations concerning the Reflexions, Refractions, and Colours of thin transparent bodies,' Newton presents the first evidence for the wavelike nature of light.

In Book II Newton also comments on the work of the Danish astronomer Olaus Roemer (1644–1710), who in 1676 measured the velocity of light by observing the time delays in successive eclipses of the Jovian moon Io as Jupiter receded from the earth. Newton's estimation of the velocity of light was more accurate than that of Roemer, who computed that light would take eleven minutes to travel from the sun to the earth, as compared to the correct value of eight minutes and twenty seconds. Newton concluded that 'Light is propagated from luminous Bodies in time, and spends about seven or eight Minutes of an Hour in passing from the Sun to the Earth.'

In Book III the opening section deals with Newton's experiments on diffraction, the bending of light when it passes from one medium to another. The remainder of the book consists of a number of hypotheses, not only on light, but on a wide variety of topics in physics and philosophy. The first edition of the *Opticks* had 16 of these Queries, the second 23, the third and fourth 31. It would seem that Newton, in the twilight of his career, was bringing out into the open some of his previously undisclosed speculations, his heritage for those who would follow him in the study of nature.

Newton died in London on 20 March 1727, four days after presiding over a meeting of the Royal Society, of which he had been President since 1703. His body lay in state until 4 April, when he was buried with great pomp in Westminster Abbey. Voltaire, writing of Newton's funeral, noted that 'He lived honoured by his compatriots and was buried like a king who had done good to his subjects.'

CHAPTER 19

The Heritage of Islamic Science

Newton paid tribute to his predecessors when he said that if he had seen farther than Descartes it was ‘by standing on the shoulders of Giants’. The colossal figures he was referring to can be identified from his works, where he gives credit to his European predecessors, most notably Copernicus, Tycho Brahe, Kepler and Galileo, and to the ancient Greeks, including Pythagoras, Empedocles, Democritus, Plato, Aristotle, Euclid, Archimedes, Apollonius, Aristarchus and Ptolemy.

But Newton makes no mention of any Islamic scientists, though surely he must have been aware that much of Greek science had been transmitted to Europe through the Islamic world. Islamic science had long passed its peak by the time the Scientific Revolution began, and, though the works of medieval Arabic philosophers, physicists, mathematicians, astronomers, engineers, astrologers and alchemists, were studied in universities, their worth and importance was for the most part overlooked in favour of contemporary scholars in western Europe. The science of ancient Greece and medieval Islam had been supplanted by the new world system that had emerged during the Scientific Revolution, and which – in very basic terms – in the two centuries after Newton would give rise to the Industrial Revolution and the atomic age.

Meanwhile scientists in the Islamic world were cut off from the revolutionary advances that were being made in the West and no longer did original work, with Islamic astronomers continuing to observe the heavens with their ancient instruments long after the invention of the telescope.

A contemporary of Tycho Brahe, the Muslim astronomer Taqi al-Din (d. ca. 1586) built the first observatory in Istanbul during the reign of

Sultan Murat III (r. 1574–95). At least one of his measurements was more accurate than that of Tycho Brahe. This was the annual motion of the sun's apogee in the celestial sphere, which he measured as 63 seconds of arc and which Tycho recorded as 45, compared to the currently accepted value of 61 seconds.

Taqi al-Din also made careful observations of the comet of 1577, and, like Tycho Brahe, he concluded that the fiery body was passing through the planetary celestial spheres. The poet 'Ala' al-Din al-Mansur, in his poem 'Concerning the Appearance of a Fiery Stellar Body,' writes that the comet appeared on the first night of Ramadan, 'passing through the nine sections of the ephemeral world ... like a turban sash over the Ursa Minor stars'.

Taqi al-Din, who was also the court astrologer, saw the comet as a sign of good fortune, and predicted that the Ottomans would be victorious in their war against the Persians. But the head of the Muslim religious hierarchy, the Sheikh ül Islam Kadızade, convinced Sultan Murat that the observatory would bring disaster to the realm by prying into the secrets of nature, though beneath this there existed subtle, yet deep political motivations. 'Ala' al-Din al-Mansur, in the last lines of his poem, describes the fate of the Istanbul observatory: 'The King of Kings summoned the Head of the Halberdiers of his bodyguard and gave him instructions for the demolition and abolition of the Observatory. Orders were given that the Admiral should ... at once wreck the observatory and pull it down from its apogee to its perigee.' And so the great observatory was destroyed, on 22 January 1580.

Islamic astronomy flowered again in the eighteenth century under Mughal rule in India. During the years 1728–34 Maharaja Sawai Jai Singh II of Jaipur (1696–1743) built five observatories for the Mughal ruler Muhammad Shah. The first of these was built at Jaipur and the others at Delhi, Benares, Ujayyin and Mathura. Jai Singh directed the Jaipur observatory for seven years, his astrologers compiling a catalogue of the celestial bodies that appears to have been based on that of Ulugh Begh's at Samarkand as well as those of Arabic and Hindu astronomers. He also was aware of the observations of European astronomers – indeed his astrologers worked with material from Europe provided by a French Jesuit priest as evidenced by the commission he received from Muhammed Shah.

> Seeing that very important affairs both regarding religion and the administration of empire depend upon these [observations]; and that in the times of the rising and setting of the planets, and seasons and eclipses of the sun and moon, many considerable disagreements of a similar nature

> were found ... since you ... have a perfect knowledge of this matter, having assembled the astronomers and geometricians of the faith of Islam, and the Brahmins and Pandits, and the astronomers of Europe, and having prepared all the apparatus of an observatory, do you so labour for the ascertaining of the point in question, that the disagreement between the calculated times of these phenomena, and the times which they were observed to happen may be rectified.

Other Islamic astronomers continued to practice their ancient science up until the beginning of modern times. Most of those in the countries and regions west of Iran worked as mosque astronomers, determining the times of the five daily occasions of prayer, observing the first appearance of the sickle moon on the western horizon after sunset to mark the beginning of a new lunar month, just as their predecessors had in Baghdad during the days of the early ʻAbbasid caliphs.

According to the Turkish historian of science Ekmeleddin Ihsanoğlu, knowledge of the Copernican theory in written Arabic form first came to the Ottoman Empire after 1664, when Tezkirici Köse Ibrahim Efendi completed his Arabic translation of the work of the French astronomer Noel Durret (d. ca. 1650), under the title *Sajanjal al-Aflak fi Ghayat al-Idrak* (*The Mirror of the Heavens and the Purpose of Perception*). A diagram in the book shows, by way of comparison, the models of Copernicus, Ptolemy and Tycho Brahe. Tezkirici says in the introduction that he showed his translation to Mehmed Efendi, Chief Astronomer under Sultan Mehmet IV. 'After examining the work quite well and not having understood anything, he said: "Europeans have many vanities similar to this one".'

Historians of science up until the mid-twentieth century were of the opinion that Islamic science reached its peak in the late medieval period and then declined rapidly, just as European science was beginning to emerge. William Cecil Dampier, whose *History of Science and its Relation with Philosophy and Religion* appeared in three editions and twelve reprints between 1929 and 1945, devotes only seven of the 574 pages of his book to Islamic science. He writes of the 'absorption of Arabic knowledge by the Latin nations' beginning at the close of the eleventh century, when, according to his view, 'the decline of Arabic and Muslim learning had set in'.

Some writers say that the decline of Arabic science was accelerated by the rise of the Mongols and their sack of Baghdad in 1258 under Hulagu, who burned down all of the city's libraries and executed the last ʻAbbasid caliph. But we have seen that two of the greatest observatories in Islam, those at Maragha and Samarkand, were established by the Mongols, the former founded by Hulagu himself the year after he sacked Baghdad.

Nevertheless, Hulagu's destruction of Baghdad was a turning point in the history of eastern Islam, for the Mongol invasion opened up the way for the westward migration of Turkish-speaking people from the steppes of central Asia. The Seljuk Turks were replaced as the dominant force in Anatolia by the Ottoman Turks, who after their conquest of Constantinople in 1453 created an empire that extended from southern Europe through the Middle East and North Africa. The Turkish historian Adnan Adıvar, writing in 1939, put forward the view (since disproved) that the Ottoman sultanate cut itself off from western science, which did not reach Turkey and the Middle East until after the collapse of the empire and the creation of the modern Turkish Republic in 1923. But we have seen that Islamic science reached a new peak under the Mongols, with the founding of the observatories at Maragha and Samarkand, and that it continued at a high level for at least another century under the Ottoman Turks before the destruction of Taqi al-Din's Istanbul observatory in 1580.

Toby E. Huff has noted that 'some of the most important scientific developments to be found in Arabic-Islamic civilisation occurred either during or after the point in time when external geopolitical factors were supposed to have caused its collapse. Thus, we should consider the most obvious internal factors regarding the development of science, and then we should examine the external and structural factors that are sociological in nature.' An examination of the outstanding work of Islamic scientists in astronomy, optics and medicine during the late medieval era leads Huff to conclude that 'The problem was not internal and scientific, but sociological and cultural. It hinged on the problem of institution building.'

Regarding institution building, Huff points out that 'Islamic law does not recognise corporate personalities, which is why cities and universities and other legally autonomous entities did not evolve there ... it was precisely the corporate (legally autonomous) nature of universities that gave them their dynamic thrust in the West and sharply set them apart from the madrasas of the Middle East.'

Few of the leading Islamic scientists were products of the madrasas, whose curriculum, except for the higher schools in law and medicine, included none of the subjects that would prepare a student to do creative work in science. Al-Ghazali was a madrasa graduate, and so, brilliant and creative though he was, his intellectual training can be seen as the background to his rejection of rational science and philosophy in favour of mysticism, an important factor in the eventual decline of Islamic science.

The Turkish historian of science Aydın Sayılı has given a penetrating analysis of the marginalisation of science in the madrasas of medieval Islam:

> The prevalence of a general picture of mild opposition or lack of encouragement is clearly reflected in the Islamic institutions of science and learning... the madras, the Islamic school of higher education, excluded systematic instruction in the secular sciences from its curriculum, and although exceptions to this general rule are found, the exceptions were short-lived and small in number. Thus the observatory, the one [institution] among them which most closely related with the non-religious sciences, experienced the greatest difficulty in becoming an integral part of the Islamic education.

The so-called 'marginality thesis' has been rejected by A. I. Sabra and other historians of science. Sabra points out that some professors in the madrasas devoted to legal studies also gave private lessons in philosophy and natural science, including medicine, and that manuscripts of these subjects were available in the libraries of madrasas and mosque schools. He points out that logic was treated by religious scholars as a necessity for argumentation in all forms of discourse.

In opposition to the marginality thesis, Sabra has instead suggested 'that what we see in the history of Islamic science is a process of assimilation ending in a complete naturalisation of the imported sciences in Muslim soil'. Sabra sees this as a 'three-stage development followed by a fourth stage of sharp decline'. The first stage, as he describes it, was 'the acquisition of ancient, particularly Greek, science and philosophy through the effort of translation from Greek and Syriac into Arabic'. The second stage saw the emergence 'of a large number of powerful Muslim thinkers whose allegiance to a comprehensive Hellenistic view of the world of matter and thought and values can be described only as a thoroughgoing commitment'. The third stage saw the assimilation of philosophical inquiry within the accepted bounds of Islamic thought, in which, according to Sabra, 'The carriers of scientific and medical knowledge now largely consisted of men who were not only Muslim by birth and faith, but who were imbued with Muslim learning and tradition, and whose conceptual framework had been produced in the process of forging a consciously Muslim outlook.'

Sabra then discusses the fourth stage, the decline of Islamic science, where he confesses that 'I do not possess a solution to the problem of decline.' His observation is that the prevailing view in Islam from al Ghazali onwards was that 'the knowledge man has been created to seek is that which brings him closer to his creator', which meant that 'not only that religious knowledge is higher in rank and more worthy of pursuit than all other forms of knowledge, but also that all other forms of knowledge must be subordinated to it'. He continues:

> The doctrines of natural science are of two sorts: those that contradict religious belief should of course be rejected, as for those that are concerned with the general properties of material objects, they can be ignored without loss. There is only one principle that should be consulted whenever one has to decide whether or not a certain branch of learning is worthy of pursuit: it is the all-important consideration that 'this world is a sowing ground for the next', and Ghazali quotes in this connection the Prophetic Tradition: 'May God protect us from useless knowledge.' The final result of this is an instrumentalist and religiously oriented view of all secular and permitted knowledge.

Sabra goes on to say that the latter part of his thesis 'is not intended as an explanation of the phenomenon of decline… It is merely meant as a relevant and possibly illuminating observation that might help in future research by directing our attention in a certain direction rather than others.' In his concluding paragraph he says that 'it should be noted that what we have here is not a general utilitarian interpretation of science, but a special view which confines scientific research to very narrow, and essentially unprogressive areas'.

Ignaz Goldziher, in a study published in 1916, suggested that in medieval Islam there was a widespread hostility among orthodox scholars toward rational science, often called 'foreign science' or 'the science of the ancients'. Because of this, he said, it is 'easily understandable why people who wanted to protect their reputations concealed their philosophical studies and pursued them under the guise of some discipline that had better standing'.

Another internal factor that led to the decline of Islamic factor was the reluctance to allow ordinary Muslims to have open access to knowledge, particularly in philosophy, religion and theology. Ibn Rushd, in his work *On the Harmony of Religion and Philosophy*, writes that 'Allegorical interpretations ought not to be expressed to the masses, nor set down in rhetorical or dialectical books.' This was why the invention of printing – as far as religious books in Arabic were concerned – was rejected by some groups in the Ottoman Empire, for it was feared that books would become cheap and fall into the hands of uneducated people who might be misled by them. Sultan Beyazit II banned the possession of printed materials in 1485, and this ban remained in effect throughout the Ottoman Empire until the nineteenth century, except for a brief interval in the early-eighteenth century.

Efforts to modernise the Ottoman army led to the establishment in 1793 of a school for artillery officers originally called the *Mühendishane-i Cedide*, or Military Engineering School. The curriculum included classes on mathematics, geography and astronomy, as evidenced by the lecture notes of Hüseyin Rifki Tamani, head teacher during the years 1806–17. But Tamani still based his astronomy teaching on the old Ptolemaic model, as he remarks at the conclusion of one lecture: 'Let it be known that the universe in appearance is a sphere and its center is the Earth ... The Sun and Moon rotate around the globe and move about the signs of the zodiac.'

Ishak Efendi (1774–1836), who became head of the *Mühendishane* in 1830, wrote a four-volume survey of contemporary scientific knowledge in Europe, including the works of Descartes and Newton. The fourth volume included 257 pages on astronomy, where he says that the Copernican theory can explain many astronomical events more easily than the old geocentric model of Ptolemy. The fourth volume of Ishak Efendi's work was first printed in 1834 in Istanbul and eleven years later it was reprinted in Cairo. During the last Ottoman century it was the principal source of knowledge in the Empire for those interested in the new science that had been developed in western Europe.

The first attempt to establish an Ottoman institution of higher learning, *Darülfünun* in Turkish, was begun during the reign of Sultan Abdül Mecit (r. 1839–61), as part of the reform movement known as the Tanzimat. The Darülfünun, which registered its first students in 1869, was reorganised in 1900 on the model of French, Austrian and German scholars, including faculties of science and medicine. After the founding of the Turkish Republic in 1923 the *Darülfünun* became the University of Istanbul and the old *Mühendishane* was reorganised as Istanbul Technical University, the first two institutions of higher learning in modern Turkey.

Another Ottoman scientific institution founded in the second half of the nineteenth century was the *Rasathane-i Amiri*, or Imperial Observatory, whose primary function was as a meteorological station. Turkish astronomers began making observations at the *Rasathane* in 1910, and early in the Turkish Republic it was moved to its present site, at Kandilli on the Asian shore of the Bosphorus. During the past century the Kandilli *Rasathane* has become a modern observatory as well as a seismological and meteorological station, all part of Bosphorus University, a Turkish institute of higher learning on the European shore of the Bosphorus, established in 1971 on the campus of the old Robert College of the University, founded in 1863.

Much of the heritage of medieval Islamic science is embodied in the hundreds of thousands of manuscripts preserved in libraries throughout the world, particularly in countries that were and continue to be centres of Muslim culture.

These collections are continually being added to, as new manuscripts are discovered, while at the same time scholars are translating, publishing and cataloguing the works of medieval Islamic scientists, most notably Fuat Sezgin's multi-volume *Geschicte des Arabischen Schrifttums*, which catalogues the work of Islamic scholars from the eleventh century onwards. Others have been publishing histories and encyclopedias of Islamic science, as well as interpreting its role in the emergence of modern science.

The most recent bio-bibliographic study is an encyclopedic work published in Istanbul in 2003 by Boris A. Rosenfeld and Ekmeleddin Ihsanoğlu, entitled *Mathematicians, Astronomers and other Scholars of Islamic Civilization and their Works (7th – 19th century)*, or MASI for short. MASI is a survey of 1,711 scientists, whose manuscripts, along with 1,376 works whose authors are unknown, are preserved in a total of 296 libraries in 50 different countries. Turkey is the most richly endowed, with 25 libraries, of which 16 are in Istanbul, the most important being the scriptorium at the Süleymaniye, which inspired me to write this book.

Most of the manuscripts are written in Arabic, but some are in Persian, Syriac, Sanskrit, Tajik, Urdu, Old Turkish, Tatar, Uzbek and other Asian languages. The subject headings under which the works are classified are mathematics, astronomy, mechanics, physics, music, mathematical geography, descriptive geography, chemistry and alchemy, mineralogy, meteorology, zoology, botany, philosophy and theology, literature and linguistics, and mysticism.

A few museums of Islamic science have been founded in recent years, and Arabic astronomical instruments are exhibited in museums of the history of science, most notably at the universities of Oxford and Cambridge, where European science emerged from its Graeco-Arabic roots.

A new Museum of Islamic Science and Technology opened in Istanbul on 24 June 2008, housed in the former imperial stables of the Topkapı Sarayı palace. Some of the exhibits were prepared by students who had taken my course in the history of science at Bosphorus University. Their exhibits all concerned the measurement of time, for our studies indicated that this was how astronomy began, and so they featured sun-dials, astrolabes and other astronomical instruments loaned by other museums in Istanbul.

One of the astrolabes was borrowed from the Kandilli Observatory, on the Asian shore of the Bosphorus directly opposite our university. The observatory has a small museum with Arabic astronomical instruments and manuscripts, many of them belonging to the sixteenth-century astronomer Taqi al-Din. The manuscripts include a copy of Taqi al-Din's treatise on the comet of 1577, the one that Tycho Brahe observed in Denmark at the beginning of his illustrious career, which would lead Kepler to create the new astronomy that helped spark the Scientific Revolution.

Then, as the vast empires of Islam declined and fell, the world forgot about its cultural heritage from Islam, whose scholars passed on Greek science, philosophy and technology to the West along with the advances they had made on their own. But now at least their accomplishments are being recognised, as the heritage of Islamic technology and science is being rediscovered by scholars and exhibited in libraries and museums around the world. Much of this reappraisal of Arabic science is being done by scholars who originated in Muslim countries, some of them Christian Arabs educated in Europe or the USA, part of the deepening interaction between Islam and the West.

These developments were part of an intellectual resurgence in Islam that revived secular education, with a new generation of Muslim scientists emerging through their contacts with the world scientific community.

This revival was most dramatically evident in the career of the Pakistani physicist Abdus Salam (1926–96), who in 1979 became the first Muslim Nobel laureate, sharing the prize in physics. Salam was born in Pakistan, where he studied before going on to Cambridge, where he received his doctorate in physics, after which he held a chair at Imperial College, London, until his retirement. Salam played a leading role in establishing the two most important government scientific agencies in Pakistan: the Atomic Energy Agency, and the Space and Upper Atmosphere Research Commission, of which he was the founding director.

He was also instrumental in the founding of five so-called Superior Science colleges to give Pakistani students a scientific education comparable to that of the West. In 1964 he founded in the International Centre for Theoretical Physics in Trieste, one of the world's leading research institutions. The founding of this centre, which has since been renamed in his honour, stemmed from his fervent belief that 'scientific thought is the common and shared heritage of mankind'.

And thus one of the great Muslim scientists of modern times completed the last stage of a cultural odyssey that had begun more than a thousand years before in Baghdad's House of Knowledge, where manuscripts from the land of the Greeks were translated into Arabic, the first stage in a journey that would take science to the West and eventually to the wider world, finally bringing it back to the lands of Islam.

NOTES

ABBREVIATIONS:

CCAP: The Cambridge Companion to Arabic Philosophy, ed. Adamson and Taylor
DSB: Dictionary of Scientific Biography, 16 vols, ed. Gillespie
EHAS: Encyclopedia of the History of Arabic Science, 3 vols, ed. Rashed
TTT: Tradition, Transmission, Transformation…, ed. Ragep et al

CHAPTER 1

1	'knowledge of the sundial…', Herodotus, II, 109
1	'The Egyptians by their…', Ibid., II, 4
1	'The invention of geometry…', Ibid., II, 109
1–2	'in the modern sense…', Neugebauer, p. 80
2	'Egyptian astronomy had…', Ibid., p. 80
2	'The Egyptian calendar became…', Ibid., p. 80
2	'survived and are often…', Ibid., p. 81
4	'No astronomical texts…', Ibid., p. 14
4	'The only essential…' Ibid., p. 29
4	'has furnished us…', Ibid., p. 14
4	'tables of square…', Ibid., p. 34
4–5	'the calculation of…', Hodgkin, p.28
5	'this method became…', Neugebauer, p. 20
5	'can in many respects…', Ibid., p. 48
6	'the first signs…', Ibid., p. 100
6	'If on the 21st…', Sarton, *A History of Science*, vol. 1, p. 77
6	'The data on…', Neugebauer, p. 101
7–8	'All that we can safely…', Ibid., p. 147
8	'the terminology as…', Ibid., p. 166
8	'it seems reasonable…', Ibid., p. 167
8	'Babylonian influence is…', Ibid., p. 156

CHAPTER 2

9 ‘the land of the Greeks’, Anawati, *DSB*, vol. 15, p. 230
10 ‘supposed the elements of …’, Kirk and Raven, p. 237
11 ‘Nothing occurs at random …’, Ibid., p. 413
12 ‘he was the first …’, Plutarch, *Pericles*, iv, 4
12 ‘The sun, the moon …’, Kirk and Raven, p. 391
12 ‘saw that the …’, Plato, *Phaedo*, 98c
12 ‘Let’s study astronomy…’, Plato, *Republic*, VII, 530 b-c
13 ‘on what hypotheses the …’, Guthrie, V, p. 450
14 ‘Now intelligent action is …’, Aristotle, *Physics*, II, 8: 12–15
14 ‘a distinguished man who …’, Diogenes Laertius, v. 58
15 ‘For if one observes …’, quoted by Lloyd, *Greek Science After Aristotle*, p. 16
15 ‘had at his disposal …’, Mostafa El-Abbadi, ‘The Alexandria Library in History’, in *Alexandria, Real and Imagined*, by Anthony Hirst and Michael Silk, p. 171
17 ‘a volume equal to …’, Dijksterhuis, p. 362
17 ‘Aristarchus of Samos has, however, …’, Ibid., p. 362–63
17 ‘that he was disturbing …’, Plutarch, *Moralia*, xii, 923
19 ‘things on land and …’, Strabo, 1.1.1
20 ‘we see here …’, Neugebauer, p. 226

CHAPTER 3

25 ‘Though I am a …’, quoted by Freely, *Istanbul, the Imperial City*, p. 78
26 ‘a man eloquent and …’, Clagett, *Greek Science in Antiquity*, p.181
26 ‘admirable introduction to the …’, O’Leary, *How Greek Science Passed to the Arabs*, p. 69
27 ‘These texts are based …’ Morelon, in *EHAS*, vol. 1, p. 9
27 ‘their valuable methods of …’, Boyer, p. 238
27 ‘I only wish to …’, Ibid, p. 238
28 ‘books by Aristotle …’, Gutas, *Greek Thought, Arabic Culture*, p. 30
28 ‘motivated by the belief …’, Ibid., p. 25
28 ‘He had in his retinue …’, Ibid. p. 30
29 ‘he mingled elements from …’, quoted by Gutas, *Greek Thought, Arabic Culture*, p. 114
29 ‘over the centuries …’, Gutas, *Greek Thought, Arabic Culture*, p. 114
29 ‘That his text survived …’, Saliba, *A History of Arabic Astronomy*, p. 72
30 ‘The people of every age …’, Gutas, *Greek Thought, Arabic Culture*, p. 46
30 ‘mistress of all sciences’, Ibid., p. 108
30 ‘to renew this useful science …’, Ibid., pp. 180–81
30 ‘Stephanus brought with him …’, Ibid., p. 181
30–1 ‘after a hiatus of …’, Ibid., p. 181

31	‘as an expression of …’, Ibid., p. 185
32	‘This was the reason …’, Ibid., p. 115
32	‘And fire which burns …’, Al-Hassan and Hill, p. 141
33	‘one of the centres …’, O’Leary, *How Greek Science Passed to the Arabs*, p. 156
33	‘From Marw came …’, Ibid., p. 156
33	‘Some of the astronomical …’, Ibid., p. 157
33	‘the varying lengths …’, Gutas, *Greek Thought, Arabic Culture*, p. 111
34	‘The ancient city…’, Pingree, *DSB*, vol. 1, p. 32
34	‘In this effort …’, Ibid., *DSB*, vol. 1, p. 33
34	‘to restore to mankind …’, Ibid., *DSB*, vol. 1, p. 32
34–5	‘In these writings …’, Ibid., *DSB*, vol. 1, p. 35
35	‘And Harun, amid the pomp …’, Clot, p. 35

CHAPTER 4

36	‘he translated from Persian …’, Gutas, *Greek Thought, Arabic Culture*, p. 55
36	‘It was a library…’, Ibid., p. 58
36	‘Under al-Ma’mun it seemed …’, Ibid., p. 58–9
36–7	‘was certainly not a center…’, Ibid., p. 59
37	‘caliphal authority at the …’, Ibid., p. 99
37	‘Al Ma’mun dreamed that …’, Ibid., p. 98
37	‘was employed full-time …’, Ibid., p. 58
38	‘encouraged me to compose …’, Ibid., p. 113
38	‘The first thing which …’, Boyer, p. 253
38	‘We have said enough …’, Ibid., p. 254
38	‘It may be that mathematics …’ O’Leary, *How Greek Science Passed to the Arabs*, p. 154
38	‘Certainly the earliest Arab …’, Ibid., p. 154
40	‘for full-time translation’, Gutas, *Greek Thought, Arabic Culture*, 133
40	‘What makes the people …’, Anawati, DSB, vol. 15, p. 230
41	‘He went to the bath …’, Hugh Kennedy, *The Court of the Caliphs*, p. 255
41	‘I sought for it …’, Anawati, *DSB*, vol. 15, p. 230
41	‘I translated it when …’, Ibid., *DSB*, vol. 15, p. 230
42	‘These are the books …’, Iskandar, *DSB*, vol. 15, p. 235
43	‘advised them to claim …’ O’Leary, *How Greek Science Passed to the Arabs*, p. 177–78
43	‘The story is obviously apocryphal …,’ Ibid., p. 173
43	‘how the Harranites came …’, Ibid., p. 173
43	‘was originally a money-changer…’, Ibid., p. 173
43	‘the supreme philosopher among …’ Thorndike, vol. I, p. 661
44–5	‘As well as the error…’, Morelon, *EHAS*, vol. I, p. 29
45	‘Handbook for manufacturing …’, Ibid., p. 55

46 'We are the heirs and offspring ...', Rozenfeld and Ihsanoğlu, p. 56
46 'a certain great noble ...', Thorndike, vol. I, p. 65
47 'the world's greatest city...', Clot, p. 197
47 'For you must know...', Ibid., p. 216
47 'See you not how...', Hugh Kennedy, *The Court of the Caliphs*, p. 63

CHAPTER 5

49 'Knowledge of the first ...', Klein-Franke, in Nasr and Leaman, p. 169
49 'We should not be ...', Walzer, p. 12
49 'My principle is first ...', Ibid., p. 13
50 'The philosopher may intend ...', Adamson, in Adamson and Taylor, p. 46
51 'It is impossible for...', Ibid., p. 41
51 'The sages', he writes, 'have proved ...', Thorndike, I, p. 65
52 'The mosquitoes go out ...', Egerton, p. 143
52 'The best gift from Allah ...', Turner, p. 131
52 'In his youth, he played ...', Arberry, *The Spiritual Physick of Rhazes*, p. 1
53 'The unsurpassed physician ...', Goodman in Nasr and Leaman, p. 198
55 'When shall it be ...', Nasr, *Science and Civilization in Islam*, p. 206
55 'I have never gone ...', Ibid., p. 200
55 'He used to sit ...', Ibid., p. 201
55–6 'Truly I know not ...', Arberry, *The Spiritual Physick of Rhazes*, p. 7
56 'After this', according to ...', Mahdi, *DSB*, vol. 4, p. 523
57 'The book can be ...', Ibid., p. 55
57 'Some men need ...', Reisman, in Adamson and Taylor, pp. 63–4
58 'Have you any proficiency...', Netton, p. 6
58 'He then drew...', Ibid., p. 6

CHAPTER 6

59 'Verily, in the creation ...', Sayılı, *The Observatory in Islam*, p. 16
59–60 'the senior of the ...', Ibid., p. 53
60 'Al Ma'mun ordered him [Khalid] to ...', Ibid., p. 53
61 'composed an important ...', Hartner, *DSB*, vol. 1, pp. 507–8
61 'We have observed it ...', Sayılı, *The Observatory in Islam*, p.97
61 'al-Battani the Harranite', Copernicus, p. 21
62 'It is impossible ...', Singh, p. 66
62 'I have a truly...', Ibid., p. 66
63 'Pleurisy is an inflamation ...', Hamarneh, *DSB*, vol. 9, p. 40
65 'After I had barely...', Kennedy, *DSB*, vol. 2, 148

68–9 ‘will be sufficient for any one ...’, Sachau, vol. 2, p. 246
69 ‘And now Islam has appeared ...’, Chelkowski, p. 113

CHAPTER 7

70 ‘when I reached the age ...’, Gutas, *Avicenna and the Aristotelian Tradition*, p. 23
70 ‘sent me for a while ...’, Ibid., p. 24
70 ‘who claimed to be ...’, Ibid., p. 24
70 ‘took leave of me’, Ibid., p. 27
70 ‘I occupied myself ...’, Ibid., p. 27
70 ‘Next I desired [to learn] medicine ...’, Ibid., p. 27
71 ‘The next year and a half ...’, Ibid., pp. 27–8
71 ‘but did not understand ...’, Ibid., p. 28
71 ‘I rejoiced at this ...’, Ibid., p. 28
71 ‘So that by...’, Ibid., p. 29
71 ‘As a matter of fact, ...’, Ibid., p. 82
71 ‘by means of which ..., Ibid., pp. 16–17
71 ‘This faculty... does not ...’, Ibid., p. 17
71 ‘divine inspiration ... as in ...’, Ibid., p. 17
71 ‘through syllogisms and ...’, Ibid., p. 17
72 ‘None shall gain ...’, Ibid., p. 19
72 ‘all the sciences ...’, Goodman, *Avicenna*, p. 18
72 ‘asked me to comment ...’, Gutas, *Avicenna and the Aristotelian Tradition*, p. 94
72 ‘Then my father died ...’, Ibid., pp. 29–30
72 ‘From this point ...’, Afnan, pp. 64–5
72 ‘amateur of these sciences’, Ibid., p. 98
73 ‘he introduced ten new...’, Ibid., p. 71
73 ‘One of the glories ...’, Ibid., p. 66
73 ‘contains the marrow...’, Gutas, *Avicenna and the Aristotelian Tradition*, p. 99
73 ‘loaded with many costly...’, Afnan, p. 66
73 ‘fearing for themselves ...’, Ibid., p. 67
73 ‘if you agree that ...’, Ibid., p. 68
74 ‘Aristotle’s oeuvre as a ...’, Gutas, *Avicenna and the Aristotelian Tradition*, p. 205
74 ‘will help remove ...’, Ibid., p. 205
74 ‘I would read the *Shifa* ...,, Afnan, p. 68
74 ‘That I go in ...’, Goodman, *Avicenna*, p. 29
74 ‘without having any book ...’, Arberry, ‘Avicenna: His Life and Times’, in Wickens, pp. 22–3
74 ‘Each day he wrote ...’, Ibid. pp. 22–3
75 ‘All three are highly...’, Hughes, pp. 2–3

76	‘because he saw that …’, Goodman, *Avicenna*, p. 33
76	‘If the year were 1900 …’, Urquhart, John, ‘How Islam changed medicine …’, in *British Medical Journal* 332 (14 January 2006), p. 120
76	‘At court he …’, Arberry, ‘Avicenna: His Life and Times’, in Wickens, pp. 23–4
76	‘He used to sit …’, Afnan, p. 77
76	‘So he finished the …’, Arberry, ‘Avicenna: His Life and Times’, in Wickens, p. 24
77	‘I then concluded …’, Ibid., pp. 54–5
77	‘petrified in the course …’, Crombie, ‘Avicenna’s Influence on the Medieval Scientific Tradition’, in Wickens, p. 97
77	‘that in many places …’, Ibid., p 97
78	‘to attain salvation …’ , Gutas, *Avicenna and the Aristotelian Tradition*, p.112
78	‘the leader of the wise …’, Morewedge, p. 76
78	‘O you who are anxious …’, Gutas, *Avicenna and the Aristotelian Tradition*, p. 140
78	‘Then I thought it …’, Ibid., p. 142
78–9	‘He once more attended …’, Arberry, ‘Avicenna: His Life and Times’, in Wickens, p. 26
79	‘a quality by which …’, Crombie, ‘Avicenna’s Influence on the Medieval Scientific Tradition’, in Wickens, p. 100
79	‘impressed force’, Ibid., p. 100
79	‘borrowed power,’ Crombie, *Medieval and Early Modern Science*, vol. 2, p. 53
79	‘*impetus impressus*’, ‘*impeto*’, *momento*’, Crombie, ‘Avicenna’s Influence on the Medieval Scientific Tradition’, in Wickens, p. 101
80	‘I think we can agree …’, Ibid., p. 101
80	‘among the sublimest …’, Arberry, ‘Avicenna: His Life and Times’, in Wickens, p. 26
80	‘Out of her lofty…’, Ibid., p. 140

CHAPTER 8

82	‘And often a latter-day…’, ‘Ahmad, *DSB*, vol. 9, p. 171
83	‘good fortune or a divine …’, Sabra, *DSB*, vol. 6, p. 190
84	‘doctrines whose matter…’, Ibid., *DSB*, vol. 6, p. 190
84	‘views on the nature …’, Sabra, *The Optics of Ibn al-Haytham*, vol. I, p. 3
84	‘recommencing the inquiry…’, Ibid., p. 5
84	‘ascend in the inquiry…’, Ibid., pp. 5–6
85	‘visual rays’, Sabra, *DSB*, vol. 6, p. 192
85	‘distinct form’, Ibid., p. 193
85	‘primary’, ‘secondary’, Ibid., p. 191
85	‘in the form of …’, Sabra, *DSB*, vol. 6, p. 191
85	‘We shall now show…’, Sabra, *The Optics of Ibn al-Haytham*, vol. I, p. 113

85–6	‘When the beholder fixes …’, Ibid., p. 229
86–7	‘In the final analysis, …’, Lindberg, *Theories of Vision from Al-Kindi to Kepler*, p. 205
87	‘learned investigators’, ‘the ancients’, Sabra, *Optics of Ibn al-Haytham*, vol. II, p. xl
87	‘thick and moist air’, Sabra, *DSB*, vol. 6, p. 195
88	‘Archimedes and Anthemius and …’, Ibid., *DSB*, vol. 6, p. 195
88	‘certain philosophers’, Sabra, *Optics of Ibn al-Haytham*, vol. II, p. xli
88	‘opacity’, Ibid., vol. II p. xli
89	‘more truly descriptive’, Sabra, *DSB*, vol. 6, p. 198
89	‘Commentary and Summary of …’, Sabra, *Optics of Ibn al-Haytham*, vol. II, p. xxxv
89	‘just as objects placed …’, Ibid., vol. II, p. xxxv
89	‘deeper… and therefore it …’, Ibid., vol. II, p. xxxv
90	‘scientific intuition’, Sabra, *DSB*, vol. 6, p. 203

CHAPTER 9

92	‘I have acquired a high …’, Johnson, p. 187
92	‘My duties to …’, Ibid., p. 187
92	‘ill for about …’, Davidson, p 73.
92	‘I can no more …’, Ibid., p. 73
92	‘From Moses [the prophet] …’, Frank and Leaman, p. 138
93	‘interpretative comments on three …’, Ibid., p. 141
93	‘because of the great …’, Roth, p. 22
93	‘as the [Babylonian] Talmud …’, Davidson, p. 149
93	‘in exile and wandering …’, Roth, p. 26
93	‘laboured day and night …’, Davidson, p. 205
93	‘assembles the entire Oral …’, Ibid., p. 208
93	‘all the commandments that …’, Ibid., p. 232
94	‘to the extent, …’, Ibid., p. 246
94	‘the celestial sphere rotates …’, Ibid., p. 235
94	‘I guarantee that …’, Davidson, p. 429
94	‘In my larger work, …’, Maimonides, *The Guide for the Perplexed*, pp. 5, 9
95	‘Having acquired this knowledge …’, Ibid., p. 397
95	‘The hearts of the people …’, Johnson, p. 193
96	‘Life is short, …’, Davidson, p. 440
96	‘from Galen’s words’ in ‘all …’, Ibid., p. 444
96	‘The indulgence in sexual …’, Maimonides, *The Medical Aphorisms*, vol. 2, p. 42
96	‘The brain of a camel …’, Ibid., vol. 2, pp. 113, 114, 119
97	‘art of medicine’ … ‘experience and reasoning …’, Davidson, p. 475
98	‘medication … beneficial for…’, Ibid., p. 467
98	‘electuary of Mithridates’, Ibid., p. 469

98	‘concedes that one select …’, Ibid., p. 463
99	‘Know, my masters, that …’, Freudenthal, p. 384 (III)
99	‘to make his body healthy and …’, Davidson, p. 233
99	‘Galen’s medicine is only…’, Johnson, p. 186
100	‘second Ibn Sina’, Nasr, *Islamic Science, An Illustrated Study,* p. 190
100–1	‘When the blood has …’, Nasr, *Science and Civilization in Islam*, p. 213–14
101	‘The heart has four…’, quoted by Huff, p. 177

CHAPTER 10

103	‘I was unable to …’, Youschkevitch, *DSB*, vol. 7, p. 325
104	‘One of the mathematical …’, Rashed and Vahabzadeh, p. 11
104	‘Whoever thinks algebra is …’, Boyer, p. 265
105	‘I have written a book …’, Youschkevitch, *DSB*, vol. 7, p. 325
106	‘Ah, but my Computations, …’, Khayyam, p. 101
106	‘One of the most …’, Al-Hassan and Hill, p. 27
106	‘This just balance is …’, Hall, *DSB*, vol. 7, p. 340
107	‘In design and operation …’, Al-Jazari, p. 9
108	‘I was in his presence …’, Ibid., p. 15
108	‘followed the method …’, Ibid., p. 17
108	‘Above the door…’, Ibid., p. 18
109	‘and the sound is …’, Ibid., p. 18
109	‘This happens at the end …’, Ibid., p. 18
109	‘I have never come …’, Ibid., p. 83
109	‘Near its foot is …’, Ibid., p. 83
110	‘The wick is lit …’, Ibid., p. 83
110	‘A goblet that arbitrates …’, Ibid., p. 94
110	‘If a mere 5 *dirhams* …’, Ibid., p. 94
111	‘And so on up …’, Ibid., p. 137
111	‘It is a fountain in a …’, Ibid., p 157
111	‘It is an instrument …’, Ibid., p. 170
111	‘The ropes go over…’, Ibid., p. 182
111–12	‘is beautiful to behold, …’, Ibid., p. 182
112	‘A lock for locking a chest …’, Ibid., p. 199
112	‘It is interesting to observe …’, Ibid., p. 274
112	‘If the observer forgets …’, Ibid., p. 204
112	‘one of the earliest manuals …’, Ibid., p. 279
112	‘He was a master craftsman, …’, Ibid., p. 279

CHAPTER 11

113	‘historians have acknowledged the …’, Al-Hassan and Hill, p. 280
113	‘When people speak of …’, Ibid., p. 280

114 ‘It is still in …’, Ibid., p. 40
114 ‘To cite but a …’, Ibid., p. 30
114 ‘Although the machine is …’, Ibid., p. 40
115 ‘that it was invented …’, Hill, *Islamic Science and Engineering*, p. 97
115 ‘Tidal mills were in …’, Al-Hassan and Hill, p. 53
115 ‘in every province of …’, Ibid., p. 54
115 ‘Paper mills were introduced …’, Ibid., p. 54
115 ‘the history of windmills …’, Needham, vol. 4, part 2, p. 556
115 ‘are commonly used by…’, Al-Hassan and Hill, p. 54
115 ‘this must surely have …’, Needham, vol. 4, part 2, p. 561
116 ‘Al-Jazari’s clocks are …’, Al-Hassan and Hill, p. 58
116 ‘… he described the construction …’, Ibid., p. 59
117 ‘To convert mercury into …’, Nasr, *Science and Civilization in Islam*, p. 267
117 ‘vessels carrying trade sail …’, Al-Hassan and Hill, p. 145
117 ‘wells were dug in …’, Ibid., p. 145
118 ‘On present evidence it …’, Ibid., p. 138
118 ‘In the same way…’, Ibid., p. 140
118 ‘Take equal parts of …’, Ibid., p. 149
118 ‘Soap manufacture became an …’, Ibid., p. 150
118 ‘… the secrets of Syrian …’, Ibid., p. 153
119 ‘The geographical distribution of …’, Smith, p. 14
119 ‘an interesting anticipation of …’, Ibid., p. 33
120 ‘installed siege engines …’, Al-Hassan and Hill, p. 112
121 ‘Arabic sources report that …’, Ibid., p. 191
121 ‘factories for paper-making …’, Ibid., p. 191
121 ‘Only later did paper-making …’, Ibid., p. 191

CHAPTER 12

123 ‘the bride of al-Andalus’, Hillenbrand, ‘The Ornament of the World’, in Jayussi, *The Legacy of Muslim Spain*, p. 118
123 ‘in four things Cordoba’, Ibid., p. 118
126 ‘one of the books of the Christians,’ Vernet and Samso, ‘Development of Arabic Science in Andalusia’, in *EHAS*, vol. 1, p. 246
126 ‘Too much branching and …’, Hamarneh, *DSB*, vol. 14, p. 584
126 ‘Only by repeated visits,’ Ibid., p. 585
127 ‘the bringer of joy and …’, Ibid., p. 585
127 ‘applied himself …’, Vernet and Samso, ‘Development of Arabic Science in Andalusia’, in *EHAS*, vol. 1, p. 254
127 ‘the author of …’, Ibid., vol. 1, p. 254
127 ‘very wise … philosopher…’, Thorndike, vol. II, p. 813
127 ‘a compendium of magic, …’, Vernet, *DSB*, vol. 9, pp. 39–40
127 ‘confused compilation of extracts’, Thorndike, vol. II, p. 815
128 ‘The virtue of the stone …’, Dunlop, pp. 78–9

128 ‘a serious illness’, Menocal, *The Ornament of the World*, p. 112
128 ‘Love, may God honor you …’, Ibid., p. 112
128 ‘I have observed women’, Menocal, *The Literature of Al-Andalus*, p. 238
128 ‘women taught me …’, Ibid., p. 238
128–29 ‘first sources of all …’, Pavlin, ‘Sunni *kalam* and theological controversies’, Nasr and Leaman, *History of Islamic Philosophy*, p. 108
129 ‘the reality of things …’, Ibid., p. 108
129 ‘In this book I …’, Hernandez, ‘Islamic Thought in the Iberian Peninsula’, in Jayussi, *The Legacy of Modern Spain*, p. 783
129 ‘to explain what’, Dold-Samplonius and Hermelink, *DSB*, vol. 7, p. 82
129 ‘There is no method …’, Ibid., *DSB*, vol. 7, p. 83
130 ‘which systematized trigonometry…’, R. P. Lorch, *DSB*, vol. 7, p. 38
130 ‘egregious calumniator of …’, R. P. Lorch, *DSB*, vol. 7, p. 39
131 ‘His tables Toletanes …’, Chaucer, *Canterbury Tales*, ‘The Franklin’s Tale’, 545–56

CHAPTER 13

134 ‘was so preoccupied with …’, Goodman, in Nasr and Leaman, *History of Islamic Philosophy*, p. 297
135 ‘combined the songs of …’, Monroe, ‘Zajal and Muwashshaha: Hispano-Arabic Poetry and the Romance Tradition’, in Jayussi, *The Legacy of Muslim Spain*, p. 412
135 ‘Wise Men of India’, Tony Levy, in Ragep, F. Jamil, and Sally P. Ragep with Steven Livesey (eds.) *Tradition, Transmission, Transformation*, p. 75
136 ‘long period of study…’, *Crombie, Medieval and Early Modern Science*, vol. 1, p. 10
136 ‘something new from …’, Ibid.
136 ‘better to attribute all …’, Ibid., vol. 1, p. 26
136 ‘I do not detract …’, Ibid., vol. 1, p. 26
136 ‘the opinions of the …’, Haskins, p. 41
137 ‘this pearl of philosophy…’, Thorndike, vol. II, p. 270
139 ‘there, seeing the abundance …’, Lemay, *DSB*, vol. 15, p. 174
139 ‘wiser philosophers of the …’, Haskins, p. 127
142 ‘If you live among …’, Ahmad, *DSB*, vol. 7, p. 8
142 ‘the wonder of the world’, Kantorowicz’, p. 356
142 ‘baptised sultans’, Haskins, p. 243
143 ‘classified in order, …’, Masson, *Frederich II of Hohenstaufen: A Life*, London, 1957, p. 224
143 ‘We have followed Aristotle …’, Ibid., p. 216
143 ‘I have heard from …’, Ibid., p. 112
143 ‘with the new Indian …’, Vogel, *DSB*, vol. 4, p. 604
144 ‘How many pairs …’, Boyer, p. 287
144 ‘the late Theodore …’, Haskins, p. 247

CHAPTER 14

146	‘By my solitary reading…’, Watt, *The Faith and Practice of Al-Ghazali*, pp. 29–30
146–47	‘We must therefore reckon…’, Ibid., p. 32
147	‘philosophical sciences’, Ibid., p. 32
147	‘connected with religious matters, …’, Ibid., p. 33
147	‘The basis of all these…’, Ibid., pp. 36–7
147	‘most of the errors…’, Ibid., p. 37
147	‘They are unable to…’, Ibid., pp. 37–8
147	‘By the time I…’, Ibid., pp. 43–4
147	‘I knew that the…’, Ibid., p. 54
147	‘Everything which God apportions…’, Campanini, in Nasr and Leaman, p. 267
149	‘the examination of the…’, Fakhry, *A History of Islamic Philosophy*, p. 289
149	‘without which the faith…’, Ibid., p. 289
150	‘At one moment the…’, Leaman, *Averroes and His Philosophy*, p. 16
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150	‘In the same way...’, Ibid., p. 17
151	‘he explained that the…’, Arnaldez, *DSB*, vol. 12, p. 7b
151	‘We affirm definitely that…’, Taylor, ‘Averroes…’, in Adamson and Taylor, p. 186
152	‘In my youth I…’, Arnaldez, *DSB*, vol. 12, p. 3
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153	‘And you know that...’, Ibid., p. 54
154	‘Our society allows no scope’, Robert Hillenbrand, ‘The Ornament of the World,’ in Jayussi, *The Legacy of Muslim Spain*, p. 122

CHAPTER 15

155	‘undoubtedly the greatest work…’, Ibn Khaldun, *Muqaddimah*, p. viii
155	‘The various kinds of science…’, Ibid., p. 333
155	‘God distinguished man…’, Ibid., p. 333
155	‘These cities have never...’, Ibid., p. 341
157	‘But when the center of the…’, Saliba, *A History of Arabic Astronomy*, p. 123

158 ‘he expounds a philosophical…’, Nasr, *DSB*, vol. 13, p. 511
158 ‘one of the most…’, Ibid., 509
158 ‘the first in history…’, Ibid., p. 510
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163 ‘… al-Shirwani … attests to …’, Saliba, *A History of Arabic Astronomy*, pp. 45–6

CHAPTER 16

164 ‘metaphysics of light’, Crombie, *Robert Grosseteste and the Origins of Experimental Science*, p. 128
165 ‘multiplication of species’, Ibid., pp. 109–10
165 ‘… An optics book…’, Lorris and Meun, *The Romance of the Rose*, p. 183
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167 ‘in the things of…’, Thorndike, vol. II, p. 144
167 ‘Every multiplication is either…’, Ibid., vol. II, p. 144
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169 ‘of corporeal influences sensible…’, Ibid., p. 214
169 ‘there is something wonderful…’, Minio-Paluello, *DSB*, vol. 9, p. 435
169 ‘that a globe of…’, Wallace, *DSB*, vol. 4, p. 93
171 ‘the rebirth of trigonometry’, Boyer, p. 308

CHAPTER 17

172 ‘this remote corner of…’, Copernicus, Preface, p. 5
173 ‘a manuscript of six…’, Gassendi, p. 140
173 ‘to the meridian of…’, Rosen, *DSB*, vol. 3, 402
173 ‘the apparent motion of…’, Rosen, *Commentariolus, in Three Copernican Treatises*, p. 57
173 ‘unable to account for…’, Ibid., p. 57
173 ‘eccentrics and epicycles, …’, Ibid., p. 57
173 ‘in which everything would…’, Ibid., pp. 57–8
173 ‘this very difficult and…’, Ibid., p. 58
173 ‘fewer and much simpler…’, Ibid., p. 58

174 'imperceptible in comparison to …', Ibid., p. 58
174 'the apparent retrograde and …', Ibid., p. 59
174 'the motion of the…', Ibid, p. 58
174 'The celestial spheres are …', Ibid., pp. 59–60
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176 'He had lost his …', Armitage, *Sun Stand Thou Still*, p. 127
176 'The sun stood still …', Joshua X, 12–14
176 'People give ear to …', Kuhn, p. 191
176 'I can reckon easily…', Copernicus, p. 2
177 'I myself think that …', Ibid., pp. 19–20
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180 'How Copernicus learned of …', Ibid., p. 130
180 'All that someone …', Saliba, *Islamic Science and the Making of the European Renaissance*, p. 193

CHAPTER 18

189 'Copernicus … affirmeth …', Kuhn, p. 186
183 'a still unexhausted treasure …', Caspar, p. 64
184 'Have faith, Galilii …', Koestler, p. 364
184 'although he knew…', Ferguson, p. 284
185 'Medicean Stars', Galileo, *The Starry Messenger*, in *Discoveries and Opinions of Galileio*, translated by Stillman Drake, p. 21
186 'necessary for the contemplation …', Caspar, p. 296
188 'foolish and absurd …', Armitage, *Copernicus and Modern Astronomy*, p. 189
188 'it would still be …', Galileo, *Dialogue Concerning the Two Chief World Systems, Ptolemaic and Copernican*, p. 464
188 'Your Galileo has ventured …', De Santillana, p. 191
188 'had altogether given rise …', Koestler, p. 503
189 'All this was in …', Westfall, p. 143
190 'rays which make blue …', Ibid., p. 160

190 ‘extremely well pleased to…’, Manuel, p. 144
191 ‘What Descartes did was…’, Westfall, p. 274
191 ‘what he thought the…’, Ibid., p. 403
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192 ‘corrected by the author’s…’, Newton, *Opticks*, p. lxxvii
192 ‘My design in this…’, Ibid., p. 1
193 ‘the oldest and most…’, Ibid., p. 369
193 ‘Light is propagated…’, Ibid., p. 277
193 ‘He lived honoured by…’, Voltaire, p. 69

CHAPTER 19

194 ‘By standing on the…’, Westfall, p. 274
195 ‘passing through the nine…’, Sayılı, *The Observatory in Islam*, p. 290
195 ‘The King of Kings…’, Ibid., p. 293
195–96 ‘Seeing that very important…’, Ibid., p. 360
196 ‘After examining the work…’ Ihsanoğlu, ‘Introduction of Western Science to the Ottoman World…’, in *Transfer of Modern Science to the Muslim World*, p. 67
196 ‘absorption of Arabic knowledge…’, Dampier, p. 82
197 ‘some of the most…’, Huff, p. 208
197 ‘The problem was not…’, Ibid., p. 212
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198 ‘The acquisition of ancient,…’, Ibid., p. 19
198 ‘of a large number…’, Ibid., p. 19
198 ‘The carriers of scientific…’, Ibid., p. 20
198 ‘I do not possess…’, Ibid., p. 22
198 ‘the knowledge man has…’, Ibid., p. 22
198–99 ‘not only that religious…’, Ibid., p. 23
199 ‘The doctrines of natural…’, Ibid. p. 23
199 ‘is not intended…’, Ibid., p. 24
199 ‘it should be noted…’, Ibid., p. 25
199 ‘easily understandable why…’, Goldhizer, p. 190
199 ‘Allegorical interpretations ought…’, Huff, p. 223
200 ‘Let it be known…’, Ihsanoğlu, ‘Introduction of Western Science to the Ottoman World…’, in *Transfer of Modern Science to the Muslim World*, p. 67
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INDEX