HISTORY OF SCIENCE

Volume 1

Benjamin Kent

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Chapter 1

Introduction

The **history of science** covers the development of science from ancient times to the present. Science is an empirical, theoretical, and procedural knowledge about the universe, produced by scientists who formulate testable explanations and predictions based on their observations. There are three major branches of science: natural, social, and formal.

The earliest roots of science can be traced to Ancient Egypt and Mesopotamia in around 3000 to 1200 BCE. Their contributions to mathematics, astronomy, and medicine entered and shaped Greek natural philosophy of classical antiquity, whereby formal attempts were made to provide explanations of events in the physical world based on natural causes. After the fall of the Western Roman Empire, knowledge of Greek conceptions of the world deteriorated in Latin-speaking Western Europe during the early centuries (400 to 1000 CE) of the Middle Ages, but continued to thrive in the Greek-speaking Eastern Roman (or Byzantine) Empire. Aided by translations of Greek texts, the Hellenistic worldview was preserved and absorbed into the Arabic-speaking Muslim world during the Islamic Golden Age. The recovery and assimilation of Greek works and Islamic inquiries into Western Europe from the 10th to 13th century revived the learning of natural philosophy in the West.

Natural philosophy was transformed during the Scientific Revolution in 16th- to 17th-century Europe, as new ideas and discoveries departed from previous Greek conceptions and traditions. The New Science that emerged was more mechanistic in its worldview, more integrated with mathematics, and more reliable and open as its knowledge was based on a newly defined scientific method. More "revolutions" in subsequent centuries soon followed. The chemical revolution of the 18th century, for instance, introduced new quantitative methods and measurements for chemistry. In the 19th century, new perspectives regarding the conservation of energy, age of the Earth, and evolution came into focus. And in the 20th century, new discoveries in genetics and physics laid the foundations for new subdisciplines such as molecular biology and particle physics. Moreover, industrial and military concerns as well as the increasing complexity of new research endeavors soon ushered in the era of "big science," particularly after the Second World War.

Prehistoric times

In prehistoric times, knowledge and technique were passed from generation to generation in an oral tradition. For instance, the domestication of maize for agriculture has been dated to about 9,000 years ago in southern Mexico, before the development of writing systems. Similarly, archaeological evidence indicates the development of astronomical knowledge in preliterate societies.

The oral tradition of preliterate societies had several features, the first of which was its fluidity. New information was constantly absorbed and adjusted to new circumstances or community needs. There were no archives or reports. This fluidity was closely related to the practical need to explain and justify a present state of affairs. Another feature was the tendency to describe the universe as just sky and earth, with a potential underworld. They were also prone to identify causes with beginnings, thereby providing a historical origin with an explanation. There was also a reliance on a "medicine man" or "wise woman" for healing, knowledge of divine or demonic causes of diseases, and in more extreme cases, for rituals such as exorcism, divination, songs, and incantations. Finally, there was an inclination to unquestioningly accept explanations that might be deemed implausible in more modern times while at the same time not being aware that such credulous behaviors could have posed problems.

The development of writing enabled humans to store and communicate knowledge across generations with much greater accuracy. Its invention was a prerequisite for the development of philosophy and later science in ancient times. Moreover, the extent to which philosophy and science would flourish in ancient times depended on the efficiency of a writing system (e.g., use of alphabets).

Earliest roots

The earliest roots of science can be traced to Ancient Egypt and Mesopotamia in around 3000 to 1200 BCE.

Ancient Egypt

Number system and geometry

Starting in around 3000 BCE, the ancient Egyptians developed a numbering system that was decimal in character and had orientated their knowledge of geometry to solving practical problems such as those of surveyors and builders. They even developed an official calendar that contained twelve months, thirty days each, and five days at the end of the year. Their development of geometry was a necessary outgrowth of surveying to preserve the layout and ownership of farmland, which was flooded annually by the Nile river. The 3-4-5 right triangle and other rules of geometry were used to build rectilinear structures, and the post and lintel architecture of Egypt.

Disease and healing

Egypt was also a center of alchemy research for much of the Mediterranean. Based on the medical papyri written in the 2500–1200 BCE, the ancient Egyptians believed that disease was mainly caused by the invasion of bodies by evil forces or spirits. Thus, in addition to using medicines, their healing therapies included prayer, incantation, and ritual. The Ebers Papyrus, written in around 1600 BCE, contains medical recipes for treating diseases related to the eyes, mouths, skins, internal organs, and extremities as well as abscesses, wounds, burns, ulcers, swollen glands, tumors, headaches, and even bad breath. The Edwin Smith papyrus, written at about the same time, contains a surgical manual for treating wounds, fractures, and dislocations. The Egyptians believed that the effectiveness of their medicines depended on the preparation and administration under appropriate rituals. Medical historians believe that ancient Egyptian pharmacology, for example, was largely ineffective. Both the Ebers and Edwin Smith papyri applied the following components to the treatment of disease: examination, diagnosis, treatment, and prognosis, which display strong parallels to the basic empirical method of science and, according to G.E.R. Lloyd, played a significant role in the development of this methodology.

Calendar

The ancient Egyptians even developed an official calendar that contained twelve months, thirty days each, and five days at the end of the year. Unlike the Babylonian calendar or the ones used in Greek city-states at the time, the official Egyptian calendar was much simpler as it was fixed and did not take lunar and solar cycles into consideration.

Mesopotamia

The ancient Mesopotamians had extensive knowledge about the chemical properties of clay, sand, metal ore, bitumen, stone, and other natural materials, and applied this knowledge to practical use in manufacturing pottery, faience, glass, soap, metals, lime plaster, and waterproofing. Metallurgy required knowledge about the properties of metals. Nonetheless, the Mesopotamians seem to have had little interest in gathering information about the natural world for the mere sake of gathering information and were far more interested in studying the manner in which the gods had ordered the universe. Biology of non-human organisms was generally only written about in the context of mainstream academic disciplines. Animal physiology was studied extensively for the purpose of divination; the anatomy of the liver, which was seen as an important organ in haruspicy, was studied in particularly intensive detail. Animal behavior was also studied for divinatory purposes. Most information about the training and domestication of animals was probably transmitted orally without being written down, but one text dealing with the training of horses has survived.

Mesopotamian medicine

The ancient Mesopotamians had no distinction between "rational science" and magic. When a person became ill, doctors prescribed magical formulas to be recited as well as medicinal treatments. The earliest medical prescriptions appear in Sumerian during the Third Dynasty of Ur (c. 2112 BC – c. 2004 BC). The most extensive Babylonian medical text, however, is the *Diagnostic Handbook* written by the *ummânū*, or chief scholar, Esagil-kin-apli of Borsippa, during the reign of the Babylonian king Adad-apla-iddina (1069–1046 BC). In East Semitic cultures, the main medicinal authority was a kind of exorcist-healer known as an*āšipu*. The profession was generally passed down from father to son and was held in extremely high regard. Of less frequent recourse was another kind of healer known as an *asu*, who corresponds more closely to a modern physician and treated physical symptoms using primarily folk remedies composed of various herbs, animal products, and minerals, as well as potions, enemas, and ointments or poultices. These physicians, who could be either male or female, also dressed wounds, set limbs, and performed simple surgeries. The ancient Mesopotamians also practiced prophylaxis and took measures to prevent the spread of disease.

Mathematics

The Mesopotamian cuneiform tablet Plimpton 322, dating to the eighteenth century BCE, records a number of Pythagorean triplets (3,4,5) (5,12,13) ..., hinting that the ancient Mesopotamians might have been aware of the Pythagorean theorem over a millennium before Pythagoras.

Astronomy and celestial divination

In Babylonian astronomy, records of the motions of the stars, planets, and the moon are left on thousands of clay tablets created by scribes. Even today, astronomical periods identified by Mesopotamian proto-scientists are still widely used in Western calendars such as the solar year and the lunar month. Using these data they developed arithmetical methods to compute the changing length of daylight in the course of the year and to predict the appearances and disappearances of the Moon and planets and eclipses of the Sun and Moon. Only a few astronomers' names are known, such as that of Kidinnu, a Chaldean astronomer and mathematician. Kiddinu's value for the solar year is in use for today's calendars. Babylonian astronomy was "the first and highly successful attempt at giving a refined mathematical description of astronomical phenomena." According to the historian A. Aaboe, "all subsequent varieties of scientific astronomy, in the Hellenistic world, in India, in Islam, and in the West—if not indeed all subsequent endeavour in the exact sciences—depend upon Babylonian astronomy in decisive and fundamental ways."

To the Babylonians and other Near Eastern cultures, messages from the gods or omens were concealed in all natural phenomena that could be deciphered and interpreted by those who are adept. Hence, it was believed that the gods could speak through all terrestrial objects (e.g., animal entrails, dreams, malformed births, or even the color of a dog urinating on a person) and celestial phenomena. Moreover, Babylonian astrology was inseparable from Babylonian astronomy.

Separate developments

Mathematical achievements from Mesopotamia had some influence on the development of mathematics in India, and there were confirmed transmissions of mathematical ideas between India and China, which were bidirectional. Nevertheless, the mathematical and scientific achievements in India and particularly in China occurred largely independently from those of Europe and the confirmed early influences that these two civilizations had on the development of science in Europe in the pre-modern era were indirect, with Mesopotamia and later the Islamic World acting as intermediaries. The arrival of modern science, which grew out of the scientific revolution, in India and China and the greater Asian region in general can be traced to the scientific activities of Jesuit missionaries who were interested in studying the region's flora and fauna during the 16th to 17th century.

India

Indian astronomy and mathematics

The earliest traces of mathematical knowledge in the Indian subcontinent appear with the Indus Valley Civilization (c. 4th millennium BCE ~ c. 3rd millennium BCE). The people of this civilization made bricks whose dimensions were in the proportion 4:2:1, considered favorable for the stability of a brick structure. They also tried to standardize measurement of length to a high degree of accuracy. They designed a ruler—the *Mohenjo-daro ruler*—whose unit of length (approximately 1.32 inches or 3.4 centimetres) was divided into ten equal parts. Bricks manufactured in ancient Mohenjo-daro often had dimensions that were integral multiples of this unit of length.

Indian astronomer and mathematician Aryabhata (476–550), in his *Aryabhatiya* (499) introduced the sine function in trigonometry. In 628 CE, Brahmagupta suggested that gravity was a force of attraction. He also lucidly explained the use of zero as both a placeholder and a decimal digit, along with the Hindu-Arabic numeral system now used universally throughout the world. Arabic translations of the two astronomers' texts were soon available in the Islamic world, introducing what would become Arabic numerals to the Islamic world by the 9th century. During the 14th–16th centuries, the Kerala school of astronomy and mathematics made significant advances in astronomy and especially mathematics, including fields such as trigonometry and analysis. In particular, Madhava of Sangamagrama is considered the "founder of mathematical analysis".

In the *Tantrasangraha* treatise, Nilakantha Somayaji's updated the Aryabhatan model for the interior planets, Mercury, and Venus and the equation that he specified for the center of these planets was more accurate than the ones in European or Islamic astronomy until the time of Johannes Kepler in the 17th century.

The first textual mention of astronomical concepts comes from the Vedas, religious literature of India. According to Sarma (2008): "One finds in the Rigveda intelligent speculations about the genesis of the universe from nonexistence, the configuration of the universe, the spherical self-supporting earth, and the year of 360 days divided into 12 equal parts of 30 days each with a periodical intercalary month.". The first 12 chapters of the *Siddhanta Shiromani*, written by Bhāskara in the 12th century, cover topics such as: mean longitudes of the planets; true longitudes of the planets; the three problems of diurnal rotation; syzygies; lunar eclipses; solar eclipses; latitudes of the planets; risings and settings; the moon's crescent; conjunctions of the planets with each other; conjunctions of the planets with the fixed stars; and the patas of the sun and moon. The 13 chapters of the second part cover the nature of the sphere, as well as significant astronomical and trigonometric calculations based on it.

Grammar

Some of the earliest linguistic activities can be found in Iron Age India (1st millennium BCE) with the analysis of Sanskrit for the purpose of the correct recitation and interpretation of Vedic texts. The most notable grammarian of Sanskrit was *Pā□ini* (c. 520–460 BCE), whose grammar formulates close to 4,000 rules for Sanskrit. Inherent in his analytic approach are the concepts of the phoneme, the morpheme and the root. The Tolkāppiyam text, composed in the early centuries of the common era, is a comprehensive text on Tamil grammar, which includes sutras on orthography, phonology, etymology, morphology, semantics, prosody, sentence structure and the significance of context in language.

Medicine

Findings from Neolithic graveyards in what is now Pakistan show evidence of proto-dentistry among an early farming culture. The ancient text Suśrutasamhitā of Suśruta describes procedures on various forms of surgery, including rhinoplasty, the repair of torn ear lobes, perineal lithotomy, cataract surgery, and several other excisions and other surgical procedures.

Politics and state

An ancient Indian treatise on statecraft, economic policy and military strategy by Kautilya and *Vi□h□ugupta*, who are traditionally identified with *Chāṇakya* (c. 350–283 BCE). In this treatise, the behaviors and relationships of the people, the King, the State, the Government Superintendents, Courtiers, Enemies, Invaders, and Corporations are analysed and documented. Roger Boesche describes the *Arthaśāstra* as "a book of political realism, a book analysing how the political world does work and not very often stating how it ought to work, a book that frequently discloses to a king what calculating and sometimes brutal measures he must carry out to preserve the state and the common good."

China

Chinese mathematics

From the earliest the Chinese used a positional decimal system on counting boards in order to calculate. To express 10, a single rod is placed in the second box from the right. The spoken language uses a similar system to English: e.g. four thousand two hundred seven. No symbol was used for zero. By the 1st century BCE, negative numbers and decimal fractions were in use and *The Nine Chapters on the Mathematical Art* included methods for extracting higher order roots by Horner's method and solving linear equations and by Pythagoras' theorem. Cubic equations were solved in the Tang dynasty and solutions of equations of order higher than 3 appeared in print in 1245 CE by Ch'in Chiu-shao. Pascal's triangle for binomial coefficients was described around 1100 by Jia Xian.

Although the first attempts at an axiomatisation of geometry appear in the Mohist canon in 330 BCE, Liu Hui developed algebraic methods in geometry in the 3rd century CE and also calculated pi to 5 significant figures. In 480, Zu Chongzhi improved this by discovering the ratio which remained the most accurate value for 1200 years.

Astronomical observations

Astronomical observations from China constitute the longest continuous sequence from any civilization and include records of sunspots (112 records from 364 BCE), supernovas (1054), lunar and solar eclipses. By the 12th century, they could reasonably accurately make predictions of eclipses, but the knowledge of this was lost during the Ming dynasty, so that the Jesuit Matteo Ricci gained much favour in 1601 by his predictions. By 635 Chinese astronomers had observed that the tails of comets always point away from the sun.

From antiquity, the Chinese used an equatorial system for describing the skies and a star map from 940 was drawn using a cylindrical (Mercator) projection. The use of an armillary sphere is recorded from the 4th century BCE and a sphere permanently mounted in equatorial axis from 52 BCE. In 125 CE Zhang Heng used water power to rotate the sphere in real time. This included rings for the meridian and ecliptic. By 1270 they had incorporated the principles of the Arab torquetum.

In the Song Empire (960–1279) of Imperial China, Chinese scholar-officials unearthed, studied, and cataloged ancient artifacts.

Inventions

To better prepare for calamities, Zhang Heng invented a seismometer in 132 CE which provided instant alert to authorities in the capital Luoyang that an earthquake had occurred in a location indicated by a specific cardinal or ordinal direction. Although no tremors could be felt in the capital when Zhang told the court that an earthquake had just occurred in the northwest, a message came soon afterwards that an earthquake had indeed struck 400 km (248 mi) to 500 km (310 mi) northwest of Luoyang (in what is now modern Gansu). Zhang called his device the 'instrument for measuring the seasonal winds and the movements of the Earth' (Houfeng didong yi), so-named because he and others thought that earthquakes were most likely caused by the enormous compression of trapped air.

There are many notable contributors to early Chinese disciplines, inventions, and practices throughout the ages. One of the best examples would be the medieval Song Chinese Shen Kuo (1031–1095), a polymath and statesman who was the first to describe the magnetic-needle compass used for navigation, discovered the concept of true north, improved the design of the astronomical gnomon, armillary sphere, sight tube, and clepsydra, and described the use of drydocks to repair boats. After observing the natural process of the inundation of silt and the find of marine fossils in the Taihang Mountains (hundreds of miles from the Pacific Ocean), Shen Kuo devised a theory of land formation, or geomorphology. He also adopted a theory of gradual climate change in regions over time, after observing petrified bamboo found underground at Yan'an, Shaanxi province. If not for Shen Kuo's writing, the architectural works of Yu Hao would be little known, along with the inventor of movable type printing, Bi Sheng (990–1051). Shen's contemporary Su Song (1020–1101) was also a brilliant polymath, an astronomer who created a celestial atlas of star maps, wrote a treatise related to botany, zoology, mineralogy, and metallurgy, and had erected a large astronomical clocktower in Kaifeng city in 1088. To operate the crowning armillary sphere, his clocktower featured an escapement mechanism and the world's oldest known use of an endless power-transmitting chain drive.

The Jesuit China missions of the 16th and 17th centuries "learned to appreciate the scientific achievements of this ancient culture and made them known in Europe. Through their correspondence European scientists first learned about the Chinese science and culture." Western academic thought on the history of Chinese technology and science was galvanized by the work of Joseph Needham and the Needham Research Institute. Among the technological accomplishments of China were, according to the British scholar Needham, early seismological detectors (Zhang Heng in the 2nd century), the water-powered celestial globe (Zhang Heng), matches, the independent invention of the decimal system, dry docks, sliding calipers, the double-action piston pump, cast iron, the blast furnace, the iron plough, the multi-tube seed drill, the wheelbarrow, the suspension bridge, the winnowing machine, the rotary fan, the parachute, natural gas as fuel, the raised-relief map, the propeller, the crossbow, and a solid fuel rocket, the multistage rocket, the horse collar, along with contributions in logic, astronomy, medicine, and other fields.

However, cultural factors prevented these Chinese achievements from developing into "modern science". According to Needham, it may have been the religious and philosophical framework of Chinese intellectuals which made them unable to accept the ideas of laws of nature:

It was not that there was no order in nature for the Chinese, but rather that it was not an order ordained by a rational personal being, and hence there was no conviction that rational personal beings would be able to spell out in their lesser earthly languages the divine code of laws which he had decreed aforetime. The Taoists, indeed, would have scorned such an idea as being too naïve for the subtlety and complexity of the universe as they intuited it.

Classical antiquity

The contributions of the Ancient Egyptians and Mesopotamians in the areas of astronomy, mathematics, and medicine had entered and shaped Greek natural philosophy of classical antiquity, whereby formal attempts were made to provide explanations of events in the physical world based on natural causes. Inquiries were also aimed at such practical goals such as establishing a reliable calendar or determining how to cure a variety of illnesses. The ancient people who were considered the first *scientists* may have thought of themselves as *natural philosophers*, as practitioners of a skilled profession (for example, physicians), or as followers of a religious tradition (for example, temple healers).

Pre-socratics

The earliest Greek philosophers, known as the pre-Socratics, provided competing answers to the question found in the myths of their neighbors: "How did the ordered cosmos in which we live come to be?" The pre-Socratic philosopher Thales (640–546 BCE) of Miletus, identified by later authors such as Aristotle as the first of the Ionian philosophers, postulated non-supernatural explanations for natural phenomena. For example, that land floats on water and that earthquakes are caused by the agitation of the water upon which the land floats, rather than the god Poseidon. Thales' student Pythagoras of Samos founded the Pythagorean school, which investigated mathematics for its own sake, and was the first to postulate that the Earth is spherical in shape. Leucippus (5th century BCE) introduced atomism, the theory that all matter is made of indivisible, imperishable units called atoms. This was greatly expanded on by his pupil Democritus and later Epicurus.

Natural philosophy

Plato and Aristotle produced the first systematic discussions of natural philosophy, which did much to shape later investigations of nature. Their development of deductive reasoning was of particular importance and usefulness to later scientific inquiry. Plato founded the Platonic Academy in 387 BCE, whose motto was "Let none unversed in geometry enter here", and turned out many notable philosophers. Plato's student Aristotle introduced empiricism and the notion that universal truths can be arrived at via observation and induction, thereby laying the foundations of the scientific method. Aristotle also produced many biological writings that were empirical in nature, focusing on biological causation and the diversity of life. He made countless observations of nature, especially the habits and attributes of plants and animals on Lesbos, classified more than 540 animal species, and dissected at least 50. Aristotle's writings profoundly influenced subsequent Islamic and European scholarship, though they were eventually superseded in the Scientific Revolution.

The important legacy of this period included substantial advances in factual knowledge, especially in anatomy, zoology, botany, mineralogy, geography, mathematics and astronomy; an awareness of the importance of certain scientific problems, especially those related to the problem of change and its causes; and a recognition of the methodological importance of applying mathematics to natural phenomena and of undertaking empirical research. In the Hellenistic age scholars frequently employed the principles developed in earlier Greek thought: the application of mathematics and deliberate empirical research, in their scientific investigations. Thus, clear unbroken lines of influence lead from ancient Greek and Hellenistic philosophers, to medieval Muslim philosophers and scientists, to the European Renaissance and Enlightenment, to the secular sciences of the modern day. Neither reason nor inquiry began with the Ancient Greeks, but the Socratic method did, along with the idea of Forms, great advances in geometry, logic, and the natural sciences. According to Benjamin Farrington, former Professor of Classics at Swansea University:

- "Men were weighing for thousands of years before Archimedes worked out the laws of equilibrium; they must have had practical and intuitional knowledge of the principles involved. What Archimedes did was to sort out the theoretical implications of this practical knowledge and present the resulting body of knowledge as a logically coherent system."

and again:

- "With astonishment we find ourselves on the threshold of modern science. Nor should it be supposed that by some trick of translation the extracts have been given an air of modernity. Far from it. The vocabulary of these writings and their style are the source from which our own vocabulary and style have been derived."

Greek astronomy

The astronomer Aristarchus of Samos was the first known person to propose a heliocentric model of the solar system, while the geographer Eratosthenes accurately calculated the circumference of the Earth. Hipparchus (c. 190 – c. 120 BCE) produced the first systematic star catalog. The level of achievement in Hellenistic astronomy and engineering is impressively shown by the Antikythera mechanism (150–100 BCE), an analog computer for calculating the position of planets. Technological artifacts of similar complexity did not reappear until the 14th century, when mechanical astronomical clocks appeared in Europe.

Hellenistic medicine

In medicine, Hippocrates (c. 460 BC – c. 370 BCE) and his followers were the first to describe many diseases and medical conditions and developed the Hippocratic Oath for physicians, still relevant and in use today. Herophilos (335–280 BCE) was the first to base his conclusions on dissection of the human body and to describe the nervous system. Galen (129 – c. 200 CE) performed many audacious operations—including brain and eye surgeries— that were not tried again for almost two millennia.

Greek mathematics

In Hellenistic Egypt, the mathematician Euclid laid down the foundations of mathematical rigor and introduced the concepts of definition, axiom, theorem and proof still in use today in his *Elements*, considered the most influential textbook ever written. Archimedes, considered one of the greatest mathematicians of all time, is credited with using the method of exhaustion to calculate the area under the arc of a parabola with the summation of an infinite series, and gave a remarkably accurate approximation of pi. He is also known in physics for laying the foundations of hydrostatics, statics, and the explanation of the principle of the lever.

Other developments

Theophrastus wrote some of the earliest descriptions of plants and animals, establishing the first taxonomy and looking at minerals in terms of their properties such as hardness. Pliny the Elder produced what is one of the largest encyclopedias of the natural world in 77 CE, and must be regarded as the rightful successor to Theophrastus. For example, he accurately describes the octahedral shape of the diamond, and proceeds to mention that diamond dust is used by engravers to cut and polish other gems owing to its great hardness. His recognition of the importance of crystal shape is a precursor to modern crystallography, while mention of numerous other minerals presages mineralogy. He also recognises that other minerals have characteristic crystal shapes, but in one example, confuses the crystal habit with the work of lapidaries. He was also the first to recognise that amber was a fossilized resin from pine trees because he had seen samples with trapped insects within them.

The development of the field of archaeology has it roots with history and with those who were interested in the past, such as kings and queens who wanted to show past glories of their respective nations. The 5th-century-BCE Greek historian Herodotus was the first scholar to systematically study the past and perhaps the first to examine artifacts.

Greek scholarship under Roman rule

During the rule of Rome, famous historians such as Polybius, Livy and Plutarch documented the rise of the Roman Republic, and the organization and histories of other nations, while statesmen like Julius Caesar, Cicero, and others provided examples of the politics of the republic and Rome's empire and wars. The study of politics during this age was oriented toward understanding history, understanding methods of governing, and describing the operation of governments.

The Roman conquest of Greece did not diminish learning and culture in the Greek provinces. On the contrary, the appreciation of Greek achievements in literature, philosophy, politics, and the arts by Rome's upper class coincided with the increased prosperity of the Roman Empire. Greek settlements had existed in Italy for centuries and the ability to read and speak Greek was not uncommon in Italian cities such as Rome. Moreover, the settlement of Greek scholars in Rome, whether voluntarily or as slaves, gave Romans access to teachers of Greek literature and philosophy. Conversely, young Roman scholars also studied abroad in Greece and upon their return to Rome, were able to convey Greek achievements to their Latin leadership. And despite the translation of a few Greek texts into Latin, Roman scholars who aspired to the highest level did so using the Greek language. The Roman statesman and philosopher Cicero (106 – 43 BCE) was a prime example. He had studied under Greek teachers in Rome and then in Athens and Rhodes. He mastered considerable portions of Greek philosophy, wrote Latin treatises on several topics, and even wrote Greek commentaries of Plato's *Timaeus* as well as a Latin translation of it, which has not survived.

In the beginning, support for scholarship in Greek knowledge was almost entirely funded by the Roman upper class. There were all sorts of arrangements, ranging from a talented scholar being attached to a wealthy household to owning educated Greek-speaking slaves. In exchange, scholars who succeeded at the highest level had an obligation to provide advice or intellectual companionship to their Roman benefactors, or to even take care of their libraries. The less fortunate or accomplished ones would teach their children or perform menial tasks. The level of detail and sophistication of Greek knowledge was adjusted to suit the interests of their Roman patrons. That meant popularizing Greek knowledge by presenting information that were of practical value such as medicine or logic (for courts and politics) but excluding subtle details of Greek metaphysics and epistemology. Beyond the basics, the Romans did not value natural philosophy and considered it an amusement for leisure time.

Commentaries and encyclopedias were the means by which Greek knowledge was popularized for Roman audiences. The Greek scholar Posidonius (c. 135-c. 51 BCE), a native of Syria, wrote prolifically on history, geography, moral philosophy, and natural philosophy. He greatly influenced Latin writers such as Marcus Terentius Varro (116-27 BCE), who wrote the encyclopedia *Nine Books of Disciplines*, which covered nine arts: grammar, rhetoric, logic, arithmetic, geometry, astronomy, musical theory, medicine, and architecture. The *Disciplines* became a model for subsequent Roman encyclopedias and Varro's nine liberal arts were considered suitable education for a Roman gentleman. The first seven of Varro's nine arts would later define the seven liberal arts of medieval schools. The pinnacle of the popularization movement was the Roman scholar Pliny the Elder (23/24–79 CE), a native of northern Italy, who wrote several books on the history of Rome and grammar. His most famous work was his voluminous *Natural History*.

After the death of the Roman Emperor Marcus Aurelius in 180 CE, the favorable conditions for scholarship and learning in the Roman Empire were upended by political unrest, civil war, urban decay, and looming economic crisis. In around 250 CE, barbarians began attacking and invading the Roman frontiers.

These combined events led to a general decline in political and economic conditions. The living standards of the Roman upper class was severely impacted, and their loss of leisure diminished scholarly pursuits. Moreover, during the 3rd and 4th centuries CE, the Roman Empire was administratively divided into two halves: Greek East and Latin West. These administrative divisions weakened the intellectual contact between the two regions. Eventually, both halves went their separate ways, with the Greek East becoming the Byzantine Empire. Christianity was also steadily expanding during this time and soon became a major patron of education in the Latin West. Initially, the Christian church adopted some of the reasoning tools of Greek philosophy in the 2nd and 3rd centuries CE to defend its faith against sophisticated opponents. Nevertheless, Greek philosophy received a mixed reception from leaders and adherents of the Christian faith. Some such as Tertullian (c. 155-c. 230 CE) were vehemently opposed to philosophy, denouncing it as heretic. Others such as Augustine of Hippo (354-430 CE) were ambivalent and defended Greek philosophy and science as the best ways to understand the natural world and therefore treated it as a handmaiden (or servant) of religion. Education in the West began its gradual decline, along with the rest of Western Roman Empire, due to invasions by Germanic tribes, civil unrest, and economic collapse. Contact with the classical tradition was lost in specific regions such as Roman Britain and northern Gaul but continued to exist in Rome, northern Italy, southern Gaul, Spain, and North Africa.

Middle Ages

In the Middle Ages, the classical learning continued in three major linguistic cultures and civilizations: Greek (the Byzantine Empire), Arabic (the Islamic world), and Latin (Western Europe).

Byzantine Empire

Preservation of Greek heritage

The fall of the Western Roman Empire led to a deterioration of the classical tradition in the western part (or Latin West) of Europe in the 400s. In contrast, the Eastern Roman or Byzantine Empire resisted the barbarian attacks, and preserved and improved the learning.

While the Byzantine Empire still held learning centers such as Constantinople, Alexandria and Antioch, Western Europe's knowledge was concentrated in monasteries until the development of medieval universities in the 12th centuries. The curriculum of monastic schools included the study of the few available ancient texts and of new works on practical subjects like medicine and timekeeping.

In the sixth century in the Byzantine Empire, Isidore of Miletus compiled Archimedes' mathematical works in the Archimedes Palimpsest, where all Archimedes' mathematical contributions were collected and studied.

John Philoponus, another Byzantine scholar, was the first to question Aristotle's teaching of physics, introducing the theory of impetus. The theory of impetus was an auxiliary or secondary theory of Aristotelian dynamics, put forth initially to explain projectile motion against gravity. It is the intellectual precursor to the concepts of inertia, momentum and acceleration in classical mechanics. The works of John Philoponus inspired Galileo Galilei ten centuries later.

The first record of separating conjoined twins took place in the Byzantine Empire in the 900s when the surgeons tried to separate a dead body of a pair of conjoined twins. The result was partly successful as the other twin managed to live for three days. The next recorded case of separating conjoined twins was several centuries later, in 1600s Germany.

Collapse

During the Fall of Constantinople in 1453, a number of Greek scholars fled to North Italy in which they fueled the era later commonly known as the "Renaissance" as they brought with them a great deal of classical learning including an understanding of botany, medicine, and zoology. Byzantium also gave the West important inputs: John Philoponus' criticism of Aristotelian physics, and the works of Dioscorides.

Islamic world

This was the period (8th–14th century CE) of the Islamic Golden Age where commerce thrived, and new ideas and technologies emerged such as the importation of papermaking from China, which made the copying of manuscripts inexpensive.

Translations and Hellenization

The eastward transmission of Greek heritage to Western Asia was a slow and gradual process that spanned over a thousand years, beginning with the Asian conquests of Alexander the Great in 335 BCE to the founding of Islam in the 7th century CE. The birth and expansion of Islam during the 7th century was quickly followed by its Hellenization. Knowledge of Greek conceptions of the world was preserved and absorbed into Islamic theology, law, culture, and commerce, which was aided by the translations of traditional Greek texts and some Syriac intermediary sources into Arabic during the 8th–9th century.

Education and scholarly pursuits

Higher education at a madrasa (or college) was focused on Islamic law and religious science and students had to engage in self-study for everything else. And despite the occasional theological backlash, many Islamic scholars of science were able to conduct their work in relatively tolerant urban centers (e.g., Baghdad and Cairo) and were protected by powerful patrons. They could also travel freely and exchange ideas as there were no political barriers within the unified Islamic state. Islamic science during this time was primarily focused on the correction, extension, articulation, and application of Greek ideas to new problems.

Advancements in mathematics

Most of the achievements by Islamic scholars during this period were in mathematics. Arabic mathematics was a direct descendant of Greek and Indian mathematics. For instance, what is now known as Arabic numerals originally came from India, but Muslim mathematicians made several key refinements to the number system, such as the introduction of decimal point notation. Mathematicians such as Muhammad ibn Musa al-Khwarizmi (c. 780–850) gave his name to the concept of the algorithm, while the term algebra is derived from *al-jabr*, the beginning of the title of one of his publications. Islamic trigonometry continued from the works of Ptolemy's *Almagest* and Indian *Siddhanta*, from which they added trigonometric functions, drew up tables, and applied trignometry to spheres and planes. Many of their engineers, instruments makers, and surveyors contributed books in applied mathematics. It was in astronomy that Islamic mathematicians made their greatest contributions. Al-Battani (c. 858–929) improved the measurements of Hipparchus, preserved in the translation of Ptolemy's *Hè Megalè Syntaxis* (*The great treatise*) translated as *Almagest*. Al-Battani also improved the precision of the measurement of the precession of the Earth's axis. Corrections were made to Ptolemy's geocentric model by al-Battani, Ibn al-Haytham, Averroes and the Maragha astronomers such as Nasir al-Din al-Tusi, Mo'ayyeduddin Urdi and Ibn al-Shatir.

Scholars with geometric skills made significant improvements to the earlier classical texts on light and sight by Euclid, Aristotle, and Ptolemy. The earliest surviving Arabic treatises were written in the 9th century by Abū Ishāq al-Kindī, Qustā ibn Lūqā, and (in fragmentary form) Ahmad ibn Isā. Later in the 11th century, Ibn al-Haytham (known as Alhazen in the West), a mathematician and astronomer, synthesized a new theory of vision based on the works of his predecessors. His new theory included a complete system of geometrical optics, which was set in great detail in his *Book of Optics*. His book was translated into Latin and was relied upon as a principal source on the science of optics in Europe until the 17th century.

Institutionalization of medicine

The medical sciences were prominently cultivated in the Islamic world. The works of Greek medical theories, especially those of Galen, were translated into Arabic and there was an outpouring of medical texts by Islamic physicians, which were aimed at organizing, elaborating, and disseminating classical medical knowledge. Medical specialties started to emerge, such as those involved in the treatment of eye diseases such as cataracts. Ibn Sina (known as Avicenna in the West, c. 980–1037) was a prolific Persian medical encyclopedist wrote extensively on medicine, with his two most notable works in medicine being the *Kitāb al-shifāʾ* ("Book of Healing") and The Canon of Medicine, both of which were used as standard medicinal texts in both the Muslim world and in Europe well into the 17th century. Amongst his many contributions are the discovery of the contagious nature of infectious diseases, and the introduction of clinical pharmacology. Institutionalization of medicine was another important achievement in the Islamic world. Although hospitals as an institution for the sick emerged in the Byzantium empire, the model of institutionalized medicine for all social classes was extensive in the Islamic empire and was scattered throughout. In addition to treating patients, physicians could teach apprentice physicians, as well write and do research. The discovery of the pulmonary transit of blood in the human body by Ibn al-Nafis occurred in a hospital setting.

Decline

Islamic science began its decline in the 12th–13th century, before the Renaissance in Europe, due in part to the Christian reconquest of Spain and the Mongol conquests in the East in the 11th–13th century. The Mongols sacked Baghdad, capital of the Abbasid caliphate, in 1258, which ended the Abbasid empire. Nevertheless, many of the conquerors became patrons of the sciences. Hulagu Khan, for example, who led the siege of Baghdad, became a patron of the Maragheh observatory. Islamic astronomy continued to flourish into the 16th century.

Western Europe

By the eleventh century, most of Europe had become Christian; stronger monarchies emerged; borders were restored; technological developments and agricultural innovations were made, increasing the food supply and population. Classical Greek texts were translated from Arabic and Greek into Latin, stimulating scientific discussion in Western Europe.

In classical antiquity, Greek and Roman taboos had meant that dissection was usually banned, but in the Middle Ages medical teachers and students at Bologna began to open human bodies, and Mondino de Luzzi (c. 1275–1326) produced the first known anatomy textbook based on human dissection.

As a result of the Pax Mongolica, Europeans, such as Marco Polo, began to venture further and further east. The written accounts of Polo and his fellow travelers inspired other Western European maritime explorers to search for a direct sea route to Asia, ultimately leading to the Age of Discovery.

Technological advances were also made, such as the early flight of Eilmer of Malmesbury (who had studied Mathematics in 11th century England), and the metallurgical achievements of the Cistercian blast furnace at Laskill.

Medieval universities

An intellectual revitalization of Western Europe started with the birth of medieval universities in the 12th century. These urban institutions grew from the informal scholarly activities of learned friars who visited monasteries, consulted libraries, and conversed with other fellow scholars. A friar who became well-known would attract a following of disciples, giving rise to a brotherhood of scholars (or *collegium* in Latin). A *collegium* might travel to a town or request a monastery to host them. However, if the number of scholars within a *collegium* grew too large, they would opt to settle in a town instead. As the number of *collegia* within a town grew, the *collegia* might request that their king grant them a charter that would convert them into a *universitas*. Many universities were chartered during this period, with the first in Bologna in 1088, followed by Paris in 1150, Oxford in 1167, and Cambridge in 1231. The granting of a charter meant that the medieval universities were partially sovereign and independent from local authorities. Their independence allowed them to conduct themselves and judge their own members based on their own rules. Furthermore, as initially religious institutions, their faculties and students were protected from capital punishment (e.g., gallows). Such independence was a matter of custom, which could, in principle, be revoked by their respective rulers if they felt threatened. Discussions of various subjects or claims at these medieval institutions, no matter how controversial, were done in a formalized way so as to declare such discussions as being within the bounds of a university and therefore protected by the privileges of that institution's sovereignty. A claim could be described as *ex cathedra* (literally "from the chair", used within the context of teaching) or *ex hypothesi* (by hypothesis). This meant that the discussions were presented as purely an intellectual exercise that did not require those involved to commit themselves to the truth of a claim or to proselytize. Modern academic concepts and practices such as academic freedom or freedom of inquiry are remnants of these medieval privileges that were tolerated in the past.

The curriculum of these medieval institutions centered on the seven liberal arts, which were aimed at providing beginning students with the skills for reasoning and scholarly language. Students would begin their studies starting with the first three liberal arts or *Trivium* (grammar, rhetoric, and logic) followed by the next four liberal arts or *Quadrivium* (arithmetic, geometry, astronomy, and music). Those who completed these requirements and received their *baccalaureate* (or Bachelor of Arts) had the option to join the higher faculty (law, medicine, or theology), which would confer an LLD for a lawyer, an MD for a physician, or ThD for a theologian. Students who chose to remain in the lower faculty (arts) could work towards a *Magister* (or Master's) degree and would study three philosophies: metaphysics, ethics, and natural philosophy. Latin translations of Aristotle's works such as *De Anima (On the Soul)* and the commentaries on them were required readings. As time passed, the lower faculty was allowed to confer its own doctoral degree called the PhD. Many of the Masters were drawn to encyclopedias and had used them as textbooks. But these scholars yearned for the complete original texts of the Ancient Greek philosophers, mathematicians, and physicians such as Aristotle, Euclid, and Galen, which were not available to them at the time. These Ancient Greek texts were to be found in the Byzantine Empire and the Islamic World.

Translations of Greek and Arabic sources

Contact with the Byzantine Empire, and with the Islamic world during the Reconquista and the Crusades, allowed Latin Europe access to scientific Greek and Arabic texts, including the works of Aristotle, Ptolemy, Isidore of Miletus, John Philoponus, Jābir ibn Hayyān, al-Khwarizmi, Alhazen, Avicenna, and Averroes. European scholars had access to the translation programs of Raymond of Toledo, who sponsored the 12th century Toledo School of Translators from Arabic to Latin. Later translators like Michael Scotus would learn Arabic in order to study these texts directly. The European universities aided materially in the translation and propagation of these texts and started a new infrastructure which was needed for scientific communities. In fact, European university put many works about the natural world and the study of nature at the center of its curriculum, with the result that the "medieval university laid far greater emphasis on science than does its modern counterpart and descendent."

At the beginning of the 13th century, there were reasonably accurate Latin translations of the main works of almost all the intellectually crucial ancient authors, allowing a sound transfer of scientific ideas via both the universities and the monasteries. By then, the natural philosophy in these texts began to be extended by scholastics such as Robert Grosseteste, Roger Bacon, Albertus Magnus and Duns Scotus. Precursors of the modern scientific method, influenced by earlier contributions of the Islamic world, can be seen already in Grosseteste's emphasis on mathematics as a way to understand nature, and in the empirical approach admired by Bacon, particularly in his *Opus Majus*. Pierre Duhem's thesis is that Stephen Tempier – the Bishop of Paris – Condemnation of 1277 led to the study of medieval science as a serious discipline, "but no one in the field any longer endorses his view that modern science started in 1277". However, many scholars agree with Duhem's view that the mid-late Middle Ages saw important scientific developments.

Medieval science

The first half of the 14th century saw much important scientific work, largely within the framework of scholastic commentaries on Aristotle's scientific writings. William of

Ockham emphasised the principle of parsimony: natural philosophers should not postulate unnecessary entities, so that motion is not a distinct thing but is only the moving object and an intermediary "sensible species" is not needed to transmit an image of an object to the eye. Scholars such as Jean Buridan and Nicole Oresme started to reinterpret elements of Aristotle's mechanics. In particular, Buridan developed the theory that impetus was the cause of the motion of projectiles, which was a first step towards the modern concept of inertia. The Oxford Calculators began to mathematically analyze the kinematics of motion, making this analysis without considering the causes of motion.

In 1348, the Black Death and other disasters sealed a sudden end to philosophic and scientific development. Yet, the rediscovery of ancient texts was stimulated by the Fall of Constantinople in 1453, when many Byzantine scholars sought refuge in the West. Meanwhile, the introduction of printing was to have great effect on European society. The facilitated dissemination of the printed word democratized learning and allowed ideas such as algebra to propagate more rapidly. These developments paved the way for the Scientific Revolution, where scientific inquiry, halted at the start of the Black Death, resumed.

Renaissance

Revival of learning

The renewal of learning in Europe began with 12th century Scholasticism. The Northern Renaissance showed a decisive shift in focus from Aristotelian natural philosophy to chemistry and the biological sciences (botany, anatomy, and medicine). Thus modern science in Europe was resumed in a period of great upheaval: the Protestant Reformation and Catholic Counter-Reformation; the discovery of the Americas by Christopher Columbus; the Fall of Constantinople; but also the re-discovery of Aristotle during the Scholastic period presaged large social and political changes. Thus, a suitable environment was created in which it became possible to question scientific doctrine, in much the same way that Martin Luther and John Calvin questioned religious doctrine. The works of Ptolemy (astronomy) and Galen (medicine) were found not always to match everyday observations. Work by Vesalius on human cadavers found problems with the Galenic view of anatomy.

Theophrastus' work on rocks, *Peri lithōn*, remained authoritative for millennia: its interpretation of fossils was not overturned until after the Scientific Revolution.

During the Italian Renaissance, Niccolò Machiavelli established the emphasis of modern political science on direct empirical observation of political institutions and actors. Later, the expansion of the scientific paradigm during the Enlightenment further pushed the study of politics beyond normative determinations. In particular, the study of statistics, to study the subjects of the state, has been applied to polling and voting.

In archeology, the 15th and 16th centuries saw the rise of antiquarians in Renaissance Europe who were interested in the collection of artifacts.

Scientific Revolution and birth of New Science

The early modern period is seen as a flowering of the European Renaissance. There was a willingness to question previously held truths and search for new answers resulted in a period of major scientific advancements, now known as the Scientific Revolution, which led to the emergence of a New Science that was more mechanistic in its worldview, more integrated with mathematics, and more reliable and open as its knowledge was based on a newly defined scientific method. The scientific revolution is a convenient boundary between ancient thought and classical physics, and is traditionally held by most historians to have begun in 1543, when the books *De humani corporis fabrica* (*On the Workings of the Human Body*) by Andreas Vesalius, and also *De Revolutionibus*, by the astronomer Nicolaus Copernicus, were first printed. The period culminated with the publication of the *Philosophiæ Naturalis Principia Mathematica* in 1687 by Isaac Newton, representative of the unprecedented growth of scientific publications throughout Europe.

Other significant scientific advances were made during this time by Galileo Galilei, Edmond Halley, Robert Hooke, Christiaan Huygens, Tycho Brahe, Johannes Kepler, Gottfried Leibniz, and Blaise Pascal. In philosophy, major contributions were made by Francis Bacon, Sir Thomas Browne, René Descartes, Spinoza and Thomas Hobbes. Christiaan Huygens derived the centripetal and centrifugal forces and was the first to transfer mathematical inquiry to describe unobservable physical phenomena. William Gilbert did some of the earliest experiments with electricity and magnetism, establishing that the Earth itself is magnetic.

Heliocentrism

The heliocentric model that was revived by Nicolaus Copernicus. The thesis of Copernicus' book was that the Earth moved around the Sun, a revival of the heliocentric model of the solar system described by Aristarchus of Samos.

Newly defined scientific method

The scientific method was also better developed as the modern way of thinking emphasized experimentation and reason over traditional considerations. Galileo ("*Father of Modern Physics*") also made use of experiments to validate physical theories, a key element of the scientific method.

Age of Enlightenment

Continuation of Scientific Revolution

The Scientific Revolution continued into the Age of Enlightenment, which accelerated the development of modern science.

Planets and orbits

The heliocentric model that was revived by Nicolaus Copernicus was followed by the first known model of planetary motion given by Johannes Kepler in the early 17th century, which proposed that the planets follow elliptical orbits, with the Sun at one focus of the ellipse.

Calculus and Newtonian mechanics

In 1687, Isaac Newton published the *Principia Mathematica*, detailing two comprehensive and successful physical theories: Newton's laws of motion, which led to classical mechanics; and Newton's law of universal gravitation, which describes the fundamental force of gravity.

Emergence of chemistry

A decisive moment came when "chemistry" was distinguished from alchemy by Robert Boyle in his work *The Sceptical Chymist*, in 1661; although the alchemical tradition continued for some time after his work. Other important steps included the gravimetric experimental practices of medical chemists like William Cullen, Joseph Black, Torbern Bergman and Pierre Macquer and through the work of Antoine Lavoisier ("father of modern chemistry") on oxygen and the law of conservation of mass, which refuted phlogiston theory. Modern chemistry emerged from the sixteenth through the eighteenth centuries through the material practices and theories promoted by alchemy, medicine, manufacturing and mining.

Circulatory system

William Harvey published *De Motu Cordis* in 1628, which revealed his conclusions based on his extensive studies of vertebrate circulatory systems. He identified the central role of the heart, arteries, and veins in producing blood movement in a circuit, and failed to find any confirmation of Galen's pre-existing notions of heating and cooling functions. The history of early modern biology and medicine is often told through the search for the seat of the soul. Galen in his descriptions of his foundational work in medicine presents the distinctions between arteries, veins, and nerves using the vocabulary of the soul.

Scientific societies and journals

A critical innovation was the creation of permanent scientific societies, and their scholarly journals, which dramatically speeded the diffusion of new ideas. Typical was the founding of the Royal Society in London in 1660. Directly based on the works of Newton, Descartes, Pascal and Leibniz, the way was now clear to the development of modern mathematics, physics and technology by the generation of Benjamin Franklin (1706–1790), Leonhard Euler (1707–1783), Mikhail Lomonosov (1711–1765) and Jean le Rond d'Alembert (1717–1783). Denis Diderot's *Encyclopédie*, published between 1751 and 1772 brought this new understanding to a wider audience. The impact of this process was not limited to science and technology, but affected philosophy (Immanuel Kant, David Hume), religion (the increasingly significant impact of science upon religion), and society and politics in general (Adam Smith, Voltaire).

Developments in geology

Geology did not undergo systematic restructuring during the Scientific Revolution but instead existed as a cloud of isolated, disconnected ideas about rocks, minerals, and landforms long before it became a coherent science. Robert Hooke formulated a theory of earthquakes, and Nicholas Steno developed the theory of superposition and argued that fossils were the remains of once-living creatures. Beginning with Thomas Burnet's *Sacred Theory of the Earth* in 1681, natural philosophers began to explore the idea that the Earth had changed over time. Burnet and his contemporaries interpreted Earth's past in terms of events described in the Bible, but their work laid the intellectual foundations for secular interpretations of Earth history.

Post-Scientific Revolution

Bioelectricity

During the late 18th century, the Italian physician Luigi Galvani took an interest in the field of "medical electricity", which emerged in the middle of the 18th century, following the electrical researches and the discovery of the effects of electricity on the human body. Galvani's experiments with bioelectricity has a popular legend which says that Galvani was slowly skinning a frog at a table where he and his wife had been conducting experiments with static electricity by rubbing frog skin. Galvani's assistant touched an exposed sciatic nerve of the frog with a metal scalpel that had picked up a charge. At that moment, they saw sparks and the dead frog's leg kicked as if in life. The observation provided the basis for the new understanding that the impetus behind muscle movement was electrical energy carried by a liquid (ions), and not air or fluid as in earlier balloonist theories. The Galvanis are credited with the discovery of bioelectricity.

Developments in geology

Modern geology, like modern chemistry, gradually evolved during the 18th and early 19th centuries. Benoît de Maillet and the Comte de Buffon saw the Earth as much older than the 6,000 years envisioned by biblical scholars. Jean-Étienne Guettard and Nicolas Desmarest hiked central France and recorded their observations on some of the first geological maps. Aided by chemical experimentation, naturalists such as Scotland's John Walker, Sweden's Torbern Bergman, and Germany's Abraham Werner created comprehensive classification systems for rocks and minerals—a collective achievement that transformed geology into a cutting edge field by the end of the eighteenth century. These early geologists also proposed a generalized interpretations of Earth history that led James Hutton, Georges Cuvier and Alexandre Brongniart, following in the steps of Steno, to argue that layers of rock could be dated by the fossils they contained: a principle first applied to the geology of the Paris Basin. The use of index fossils became a powerful tool for making geological maps, because it allowed geologists to correlate the rocks in one locality with those of similar age in other, distant localities.

Birth of modern economics

The basis for classical economics forms Adam Smith's *An Inquiry into the Nature and Causes of the Wealth of Nations*, published in 1776. Smith criticized mercantilism, advocating a system of free trade with division of labour. He postulated an "invisible hand" that regulated economic systems made up of actors guided only by self-interest. The "invisible hand" mentioned in a lost page in the middle of a chapter in the middle of the "Wealth of Nations", 1776, advances as Smith's central message. It is played down that this "invisible hand" acts only "frequently" and that it is "no part of his [the individual's] intentions" because competition leads to lower prices by imitating "his" invention. That this "invisible hand" prefers "the support of domestic to foreign industry" is cleansed—often without indication that part of the citation is truncated. The opening passage of the "Wealth" containing Smith's message is never mentioned as it cannot be integrated into modern theory: "Wealth" depends on the division of labour which changes with market volume and on the proportion of productive to Unproductive labor.

Social science

Anthropology can best be understood as an outgrowth of the Age of Enlightenment. It was during this period that Europeans attempted systematically to study human behavior. Traditions of jurisprudence, history, philology and sociology developed during this time and informed the development of the social sciences of which anthropology was a part.

19th century

The 19th century saw the birth of science as a profession. William Whewell had coined the term the term *scientist* in 1833, which soon replaced the older term *natural philosopher*.

Electricity and magnetism

In physics, the behavior of electricity and magnetism was studied by Giovanni Aldini, Alessandro Volta, Michael Faraday, Georg Ohm, and others. The experiments, theories and discoveries of Michael Faraday, Andre-Marie Ampere, James Clerk Maxwell, and their contemporaries led to the unification of the two phenomena into a single theory of electromagnetism as described by Maxwell's equations. Thermodynamics led to an understanding of heat and the notion of energy was defined.

Discovery of Neptune

In astronomy, the planet Neptune was discovered. Advances in astronomy and in optical systems in the 19th century resulted in the first observation of an asteroid (1 Ceres) in 1801, and the discovery of Neptune in 1846. In 1925, Cecilia Payne-Gaposchkin determined that stars were composed mostly of hydrogen and helium. She was dissuaded by astronomer Henry Norris Russell from publishing this finding in her PhD thesis because of the widely held belief that stars had the same composition as the Earth. However, four years later, in 1929, Henry Norris Russell came to the same conclusion through different reasoning and the discovery was eventually accepted.

Developments in mathematics

In mathematics, the notion of complex numbers finally matured and led to a subsequent analytical theory; they also began the use of hypercomplex numbers. Karl Weierstrass and others carried out the arithmetization of analysis for functions of real and complex variables. It also saw rise to new progress in geometry beyond those classical theories of Euclid, after a period of nearly two thousand years. The mathematical science of logic likewise had revolutionary breakthroughs after a similarly long period of stagnation. But the most important step in science at this time were the ideas formulated by the creators of electrical science. Their work changed the face of physics and made possible for new technology to come about such as electric power, electrical telegraphy, the telephone, and radio.

Developments in chemistry

In chemistry, Dmitri Mendeleev, following the atomic theory of John Dalton, created the first periodic table of elements. Other highlights include the discoveries unveiling the nature of atomic structure and matter, simultaneously with chemistry – and of new kinds of radiation. The theory that all matter is made of atoms, which are the smallest constituents of matter that cannot be broken down without losing the basic chemical and physical properties of that matter, was provided by John Dalton in 1803, although the question took a hundred years to settle as proven. Dalton also formulated the law of mass relationships. In 1869, Dmitri Mendeleev composed his periodic table of elements on the basis of Dalton's discoveries. The synthesis of urea by Friedrich Wöhler opened a new research field, organic chemistry, and by the end of the 19th century, scientists were able to synthesize hundreds of organic compounds. The later part of the 19th century saw the exploitation of the Earth's petrochemicals, after the exhaustion of the oil supply from whaling. By the 20th century, systematic production of refined materials provided a ready supply of products which provided not only energy, but also synthetic materials for clothing, medicine, and everyday disposable resources. Application of the techniques of organic chemistry to living organisms resulted in physiological chemistry, the precursor to biochemistry.

Age of the Earth

Over the first half of the 19th century, geologists such as Charles Lyell, Adam Sedgwick, and Roderick Murchison applied the new technique to rocks throughout Europe and eastern North America, setting the stage for more detailed, government-funded mapping projects in later decades. Midway through the 19th century, the focus of geology shifted from description and classification to attempts to understand *how* the surface of the Earth had changed. The first comprehensive theories of mountain building were proposed during this period, as were the first modern theories of earthquakes and volcanoes. Louis Agassiz and others established the reality of continent-covering ice ages, and "fluvialists" like Andrew Crombie Ramsay argued that river valleys were formed, over millions of years by the rivers that flow through them. After the discovery of radioactivity, radiometric dating methods were developed, starting in the 20th century. Alfred Wegener's theory of "continental drift" was widely dismissed when he proposed it in the 1910s, but new data gathered in the 1950s and 1960s led to the theory of plate tectonics, which provided a plausible mechanism for it. Plate tectonics also provided a unified explanation for a wide range of seemingly unrelated geological phenomena. Since 1970 it has served as the unifying principle in geology.

Evolution and inheritance

Perhaps the most prominent, controversial, and far-reaching theory in all of science has been the theory of evolution by natural selection, which was independently formulated by Charles Darwin and Alfred Wallace. It was described in detail in Darwin's book *The Origin of Species*, which was published in 1859. In it, Darwin proposed that the features of all living things, including humans, were shaped by natural processes over long periods of time. The theory of evolution in its current form affects almost all areas of biology. Implications of evolution on fields outside of pure science have led to both opposition and support from different parts of society, and profoundly influenced the popular understanding of "man's place in the universe". Separately, Gregor Mendel formulated in the principles of inheritance in 1866, which became the basis of modern genetics.

Germ theory

Another important landmark in medicine and biology were the successful efforts to prove the germ theory of disease. Following this, Louis Pasteur made the first vaccine against rabies, and also made many discoveries in the field of chemistry, including the asymmetry of crystals. In 1847, Hungarian physician Ignác Fülöp Semmelweis dramatically reduced the occurrency of puerperal fever by simply requiring physicians to wash their hands before attending to women in childbirth. This discovery predated the germ theory of disease. However, Semmelweis' findings were not appreciated by his contemporaries and handwashing came into use only with discoveries by British surgeon Joseph Lister, who in 1865 proved the principles of antisepsis. Lister's work was based on the important findings by French biologist Louis Pasteur. Pasteur was able to link microorganisms with disease, revolutionizing medicine. He also devised one of the most important methods in preventive medicine, when in 1880 he produced a vaccine against rabies. Pasteur invented the process of pasteurization, to help prevent the spread of disease through milk and other foods.

Schools of economics

Karl Marx developed an alternative economic theory, called Marxian economics. Marxian economics is based on the labor theory of value and assumes the value of good to be based on the amount of labor required to produce it. Under this axiom, capitalism was based on employers not paying the full value of workers labor to create profit. The Austrian School responded to Marxian economics by viewing entrepreneurship as driving force of economic development. This replaced the labor theory of value by a system of supply and demand.

Founding of psychology

Psychology as a scientific enterprise that was independent from philosophy began in 1879 when Wilhelm Wundt founded the first laboratory dedicated exclusively to psychological research (in Leipzig). Other important early contributors to the field include Hermann Ebbinghaus (a pioneer in memory studies), Ivan Pavlov (who discovered classical conditioning), William James, and Sigmund Freud. Freud's influence has been enormous, though more as cultural icon than a force in scientific psychology.

Modern sociology

Modern sociology emerged in the early 19th century as the academic response to the modernization of the world. Among many early sociologists (e.g., Émile Durkheim), the aim of sociology was in structuralism, understanding the cohesion of social groups, and developing an "antidote" to social disintegration. Max Weber was concerned with the modernization of society through the concept of rationalization, which he believed would trap individuals in an "iron cage" of rational thought. Some sociologists, including Georg Simmel and W. E. B. Du Bois, utilized more microsociological, qualitative analyses. This microlevel approach played an important role in American sociology, with the theories of George Herbert Mead and his student Herbert Blumer resulting in the creation of the symbolic interactionism approach to sociology. In particular, just Auguste Comte, illustrated with his work the transition from a theological to a metaphysical stage and, from this, to a positive stage. Comte took care of the classification of the sciences as well as a transit of humanity towards a situation of progress attributable to a re-examination of nature according to the affirmation of 'sociality' as the basis of the scientifically interpreted society.

Romanticism

The Romantic Movement of the early 19th century reshaped science by opening up new pursuits unexpected in the classical approaches of the Enlightenment. The decline of Romanticism occurred because a new movement, Positivism, began to take hold of the ideals of the intellectuals after 1840 and lasted until about 1880. At the same time, the romantic reaction to the Enlightenment produced thinkers such as Johann Gottfried Herder and later Wilhelm Dilthey whose work formed the basis for the culture concept which is central to the discipline. Traditionally, much of the history of the subject was based on colonial encounters between Western Europe and the rest of the world, and much of 18th- and 19th-century anthropology is now classed as scientific racism. During the late 19th century, battles over the "study of man" took place between those of an "anthropological" persuasion (relying on anthropometrical techniques) and those of an "ethnological" persuasion (looking at cultures and traditions), and these distinctions became part of the later divide between physical anthropology and cultural anthropology, the latter ushered in by the students of Franz Boas.

20th century

Science advanced dramatically during the 20th century. There were new and radical developments in the physical and life sciences, building on the progress from the 19th century.

Theory of relativity and quantum mechanics

The beginning of the 20th century brought the start of a revolution in physics. The long-held theories of Newton were shown not to be correct in all circumstances. Beginning in 1900, Max Planck, Albert Einstein, Niels Bohr and others developed quantum theories to explain various anomalous experimental results, by introducing discrete energy levels. Not only did quantum mechanics show that the laws of motion did not hold on small scales, but the theory of general relativity, proposed by Einstein in 1915, showed that the fixed background of spacetime, on which both Newtonian mechanics and special relativity depended, could not exist. In 1925, Werner Heisenberg and Erwin Schrödinger formulated quantum mechanics, which explained the preceding quantum theories.

The observation by Edwin Hubble in 1929 that the speed at which galaxies recede positively correlates with their distance, led to the understanding that the universe is expanding, and the formulation of the Big Bang theory by Georges Lemaître. Currently, general relativity and quantum mechanics are inconsistent with each other, and efforts are underway to unify the two.

Big science

In 1938 Otto Hahn and Fritz Strassmann discovered nuclear fission with radiochemical methods, and in 1939 Lise Meitner and Otto Robert Frisch wrote the first theoretical interpretation of the fission process, which was later improved by Niels Bohr and John A. Wheeler. Further developments took place during World War II, which led to the practical application of radar and the development and use of the atomic bomb. Around this time, Chien-Shiung Wu was recruited by the Manhattan Project to help develop a process for separating uranium metal into U-235 and U-238 isotopes by Gaseous diffusion. She was an expert experimentalist in beta decay and weak interaction physics. Wu designed an experiment (see Wu experiment) that enabled theoretical physicists Tsung-Dao Lee and Chen-Ning Yang to disprove the law of parity experimentally, winning them a Nobel Prize in 1957.

Though the process had begun with the invention of the cyclotron by Ernest O. Lawrence in the 1930s, physics in the postwar period entered into a phase of what historians have called "Big Science", requiring massive machines, budgets, and laboratories in order to test their theories and move into new frontiers. The primary patron of physics became state governments, who recognized that the support of "basic" research could often lead to technologies useful to both military and industrial applications.

Big Bang

George Gamow, Ralph Alpher, and Robert Herman had calculated that there should be evidence for a Big Bang in the background temperature of the universe. In 1964, Arno Penzias and Robert Wilson discovered a 3 Kelvin background hiss in their Bell Labs radiotelescope (the Holmdel Horn Antenna), which was evidence for this hypothesis, and formed the basis for a number of results that helped determine the age of the universe.

Space exploration

Supernova SN1987A was observed by astronomers on Earth both visually, and in a triumph for neutrino astronomy, by the solar neutrino detectors at Kamiokande. But the solar neutrino flux was a fraction of its theoretically expected value. This discrepancy forced a change in some values in the standard model for particle physics.

Advancements in genetics

In the early 20th century, the study of heredity became a major investigation after the rediscovery in 1900 of the laws of inheritance developed by Mendel. The 20th century also saw the integration of physics and chemistry, with chemical properties explained as the result of the electronic structure of the atom. Linus Pauling's book on *The Nature of the Chemical Bond* used the principles of quantum mechanics to deduce bond angles in ever-more complicated molecules. Pauling's work culminated in the physical modelling of DNA, *the secret of life* (in the words of Francis Crick, 1953). In the same year, the Miller–Urey experiment demonstrated in a simulation of primordial processes, that basic constituents of proteins, simple amino acids, could themselves be built up from simpler molecules, kickstarting decades of research into the chemical origins of life. By 1953, James D. Watson and Francis Crick clarified the basic structure of DNA, the genetic material for expressing life in all its forms, building on the work of Maurice Wilkins and Rosalind Franklin, suggested that the structure of DNA was a double helix. In their famous paper "Molecular structure of Nucleic Acids" In the late 20th century, the possibilities of genetic engineering became practical for the first time, and a massive international effort began in 1990 to map out an entire human genome (the Human Genome Project). The discipline of ecology typically traces its origin to the synthesis of Darwinian evolution and Humboldtian biogeography, in the late 19th and early 20th centuries. Equally important in the rise of ecology, however, were microbiology and soil science—particularly the cycle of life concept, prominent in the work Louis Pasteur and Ferdinand Cohn. The word *ecology* was coined by Ernst Haeckel, whose particularly holistic view of nature in general (and Darwin's theory in particular) was important in the spread of ecological thinking. In the 1930s, Arthur Tansley and others began developing the field of ecosystem ecology, which combined experimental soil science with physiological concepts of energy and the techniques of field biology.

Neuroscience as a distinct discipline

The understanding of neurons and the nervous system became increasingly precise and molecular during the 20th century. For example, in 1952, Alan Lloyd Hodgkin and Andrew Huxley presented a mathematical model for transmission of electrical signals in neurons of the giant axon of a squid, which they called "action potentials", and how they are initiated and propagated, known as the Hodgkin–Huxley model. In 1961–1962, Richard FitzHugh and J. Nagumo simplified Hodgkin–Huxley, in what is called the FitzHugh–Nagumo model. In 1962, Bernard Katz modeled neurotransmission across the space between neurons known as synapses. Beginning in 1966, Eric Kandel and collaborators examined biochemical changes in neurons associated with learning and memory storage in *Aplysia*. In 1981 Catherine Morris and Harold Lecar combined these models in the Morris–Lecar model. Such increasingly quantitative work gave rise to numerous biological neuron models and models of neural computation. Neuroscience began to be recognized as a distinct academic discipline in its own right. Eric Kandel and collaborators have cited David Rioch, Francis O. Schmitt, and Stephen Kuffler as having played critical roles in establishing the field.

Plate tectonics

Geologists' embrace of plate tectonics became part of a broadening of the field from a study of rocks into a study of the Earth as a planet. Other elements of this transformation include: geophysical studies of the interior of the Earth, the grouping of geology with meteorology and oceanography as one of the "earth sciences", and comparisons of Earth and the solar system's other rocky planets.

Applications

In terms of applications, a massive amount of new technologies were developed in the 20th century. Technologies such as electricity, the incandescent light bulb, the automobile and the phonograph, first developed at the end of the 19th century, were perfected and universally deployed. The first airplane flight occurred in 1903, and by the end of the century large airplanes such as the Boeing 777 and Airbus A330 flew thousands of miles in a matter of hours. The development of the television and computers caused massive changes in the dissemination of information. Advances in biology also led to large increases in food production, as well as the elimination of diseases such as polio. Computer science, built upon a foundation of theoretical linguistics, discrete mathematics, and electrical engineering, studies the nature and limits of computation. Subfields include computability, computational complexity, database design, computer networking, artificial intelligence, and the design of computer hardware. One area in which advances in computing have contributed to more general scientific development is by facilitating large-scale archiving of scientific data. Contemporary computer science typically distinguishes itself by emphasising mathematical 'theory' in contrast to the practical emphasis of software engineering.

Developments in political science

In political science during the 20th century, the study of ideology, behaviouralism and international relations led to a multitude of 'pol-sci' subdisciplines including rational choice theory, voting theory, game theory (also used in economics), psephology, political geography/geopolitics, political psychology/political sociology, political economy, policy analysis, public administration, comparative political analysis and peace studies/conflict analysis.

Keynesian and new classical economics

In economics, John Maynard Keynes prompted a division between microeconomics and macroeconomics in the 1920s. Under Keynesian economics macroeconomic trends can overwhelm economic choices made by individuals. Governments should promote aggregate demand for goods as a means to encourage economic expansion. Following World War II, Milton Friedman created the concept of monetarism. Monetarism focuses on using the supply and demand of money as a method for controlling economic activity. In the 1970s, monetarism has adapted into supply-side economics which advocates reducing taxes as a means to increase the amount of money available for economic expansion. Other modern schools of economic thought are New Classical economics and New Keynesian economics. New Classical economics was developed in the 1970s, emphasizing solid microeconomics as the basis for macroeconomic growth. New Keynesian economics was created partially in response to New Classical economics, and deals with how inefficiencies in the market create a need for control by a central bank or government.

Developments in psychology, sociology, and anthropology

Psychology in the 20th century saw a rejection of Freud's theories as being too unscientific, and a reaction against Edward Titchener's atomistic approach of the mind. This led to the formulation of behaviorism by John B. Watson, which was popularized by B.F. Skinner. Behaviorism proposed epistemologically limiting psychological study to overt behavior, since that could be reliably measured. Scientific knowledge of the "mind" was considered too metaphysical, hence impossible to achieve. The final decades of the 20th century have seen the rise of cognitive science, which considers the mind as once again a subject for investigation, using the tools of psychology, linguistics, computer science, philosophy, and neurobiology. New methods of visualizing the activity of the brain, such as PET scans and CAT scans, began to exert their influence as well, leading some researchers to investigate the mind by investigating the brain, rather than cognition. These new forms of investigation assume that a wide understanding of the human mind is possible, and that such an understanding may be applied to other research domains, such as artificial intelligence. Evolutionary theory was applied to behavior and introduced to anthropology and psychology through the works of cultural anthropologist Napoleon Chagnon and E.O. Wilson. Wilson's book *Sociobiology: The New Synthesis* discussed how evolutionary mechanisms shaped the behaviors of all living organisms, including humans. Decades later, John Tooby and Leda Cosmides would develop the discipline of evolutionary psychology.

American sociology in the 1940s and 1950s was dominated largely by Talcott Parsons, who argued that aspects of society that promoted structural integration were therefore "functional". This structural functionalism approach was questioned in the 1960s, when sociologists came to see this approach as merely a justification for inequalities present in the status quo. In reaction, conflict theory was developed, which was based in part on the philosophies of Karl Marx. Conflict theorists saw society as an arena in which different groups compete for control over resources. Symbolic interactionism also came to be regarded as central to sociological thinking. Erving Goffman saw social interactions as a stage performance, with individuals preparing "backstage" and attempting to control their audience through impression management. While these theories are currently prominent in sociological thought, other approaches exist, including feminist theory, post-structuralism, rational choice theory, and postmodernism.

In the mid-20th century, much of the methodologies of earlier anthropological and ethnographical study were reevaluated with an eye towards research ethics, while at the same time the scope of investigation has broadened far beyond the traditional study of "primitive cultures".

21st century

Higgs boson

On July 4, 2012, physicists working at CERN's Large Hadron Collider announced that they had discovered a new subatomic particle greatly resembling the Higgs boson, a potential key to an understanding of why elementary particles have mass and indeed to the existence of diversity and life in the universe. For now, some physicists are calling it a "Higgslike" particle. Peter Higgs was one of six physicists, working in three independent groups, who, in 1964, invented the notion of the Higgs field ("cosmic molasses"). The others were Tom Kibble of Imperial College, London; Carl Hagen of the University of Rochester; Gerald Guralnik of Brown University; and François Englert and Robert Brout, both of Université libre de Bruxelles.

Chapter 2

History of Scientific Method

The **history of scientific method** considers changes in the methodology of scientific inquiry, as distinct from the history of science itself. The development of rules for scientific reasoning has not been straightforward; scientific method has been the subject of intense and recurring debate throughout the history of science, and eminent natural philosophers and scientists have argued for the primacy of one or another approach to establishing scientific knowledge. Despite the disagreements about approaches, scientific method has advanced in definite steps. Rationalist explanations of nature, including atomism, appeared both in ancient Greece in the thought of Leucippus and Democritus, and in ancient India, in the Nyaya, Vaisesika and Buddhist schools, while Charvaka materialism rejected inference as a source of knowledge in favour of an empiricism that was always subject to doubt. Aristotle pioneered scientific method in ancient Greece alongside his empirical biology and his work on logic, rejecting a purely deductive framework in favour of generalisations made from observations of nature.

Some of the most important debates in the history of scientific method center on: rationalism, especially as advocated by René Descartes; inductivism, which rose to particular prominence with Isaac Newton and his followers; and hypothetico-deductivism, which came to the fore in the early 19th century. In the late 19th and early 20th centuries, a debate over realism vs. antirealism was central to discussions of scientific method as powerful scientific theories extended beyond the realm of the observable, while in the mid-20th century some prominent philosophers argued against any universal rules of science at all.

Early methodology

Ancient Egypt and Babylonia

There are few explicit discussions of scientific methodologies in surviving records from early cultures. The most that can be inferred about the approaches to undertaking science in this period stems from descriptions of early investigations into nature, in the surviving records. An Egyptian medical textbook, the Edwin Smith papyrus, (c. 1600 BCE), applies the following components: examination, diagnosis, treatment and prognosis, to the treatment of disease, which display strong parallels to the basic empirical method of science and according to G. E. R. Lloyd played a significant role in the development of this methodology. The Ebers papyrus (c. 1550 BCE) also contains evidence of traditional empiricism.

By the middle of the 1st millennium BCE in Mesopotamia, Babylonian astronomy had evolved into the earliest example of a scientific astronomy, as it was "the first and highly successful attempt at giving a refined mathematical description of astronomical phenomena." According to the historian Asger Aaboe, "all subsequent varieties of scientific astronomy, in the Hellenistic world, in India, in the Islamic world, and in the West – if not indeed all subsequent endeavour in the exact sciences – depend upon Babylonian astronomy in decisive and fundamental ways."

The early Babylonians and Egyptians developed much technical knowledge, crafts, and mathematics used in practical tasks of divination, as well as a knowledge of medicine, and made lists of various kinds. While the Babylonians in particular had engaged in the earliest forms of an empirical mathematical science, with their early attempts at mathematically describing natural phenomena, they generally lacked underlying rational theories of nature.

Classical antiquity

Greek-speaking ancient philosophers engaged in the earliest known forms of what is today recognized as a rational theoretical science, with the move towards a more rational understanding of nature which began at least since the Archaic Period (650 – 480 BCE) with the Presocratic school. Thales was the first known philosopher to use natural explanations, proclaiming that every event had a natural cause, even though he is known for saying "all things are full of gods" and sacrificed an ox when he discovered his theorem. Leucippus, went on to develop the theory of atomism – the idea that everything is composed entirely of various imperishable, indivisible elements called atoms. This was elaborated in great detail by Democritus.

Similar atomist ideas emerged independently among ancient Indian philosophers of the Nyaya, Vaisesika and Buddhist schools. In particular, like the Nyaya, Vaisesika, and Buddhist schools, the Cārvāka epistemology was materialist, and skeptical enough to admit perception as the basis for unconditionally true knowledge, while cautioning that if one could only infer a truth, then one must also harbor a doubt about that truth; an inferred truth could not be unconditional.

Towards the middle of the 5th century BCE, some of the components of a scientific tradition were already heavily established, even before Plato, who was an important contributor to this emerging tradition, thanks to the development of deductive reasoning, as propounded by his student, Aristotle. In *Protagoras* (318d-f), Plato mentioned the teaching of arithmetic, astronomy and geometry in schools. The philosophical ideas of this time were mostly freed from the constraints of everyday phenomena and common sense. This denial of reality as we experience it reached an extreme in Parmenides who argued that the world is one and that change and subdivision do not exist.

In the 3rd and 4th centuries BCE, the Greek physicians Herophilos (335–280 BCE) and Erasistratus of Chios employed experiments to further their medical research; Erasistratus at one time repeatedly weighing a caged bird, and noting its weight loss between feeding times.

Aristotle

Aristotle's inductive-deductive method used inductions from observations to infer general principles, deductions from those principles to check against further observations, and more cycles of induction and deduction to continue the advance of knowledge.

The *Organon* (Greek: Ὄργανον, meaning "instrument, tool, organ") is the standard collection of Aristotle's six works on logic. The name *Organon* was given by Aristotle's followers, the Peripatetics. The order of the works is not chronological (the chronology is now difficult to determine) but was deliberately chosen by Theophrastus to constitute a well-structured system. Indeed, parts of them seem to be a scheme of a lecture on logic. The arrangement of the works was made by Andronicus of Rhodes around 40 BCE.

The *Organon* comprises the following six works:

- The *Categories* (Greek: Κατηγορίαι, Latin: *Categoriae*) introduces Aristotle's 10-fold classification of that which exists: substance, quantity, quality, relation, place, time, situation, condition, action, and passion.
- *On Interpretation* (Greek: ΠερὶἙρμηνείας, Latin: *De Interpretatione*) introduces Aristotle's conception of proposition and judgment, and the various relations between affirmative, negative, universal, and particular propositions. Aristotle discusses the square of opposition or square of Apuleius in Chapter 7 and its appendix Chapter 8. Chapter 9 deals with the problem of future contingents.
- The *Prior Analytics* (Greek: ἈναλυτικὰΠρότερα, Latin: *Analytica Priora*) introduces Aristotle's syllogistic method (see term logic), argues for its correctness, and discusses inductive inference.
- The *Posterior Analytics* (Greek: ἈναλυτικὰὝστερα, Latin: *Analytica Posteriora*) deals with demonstration, definition, and scientific knowledge.

- The *Topics* (Greek: Τοπικά, Latin: *Topica*) treats of issues in constructing valid arguments, and of inference that is probable, rather than certain. It is in this treatise that Aristotle mentions the predicables, later discussed by Porphyry and by the scholastic logicians.
- The *Sophistical Refutations* (Greek: ΠερὶΣοφιστικῶνἘλέγχων, Latin: *De Sophisticis Elenchis*) gives a treatment of logical fallacies, and provides a key link to Aristotle's work on rhetoric.

Aristotle's *Metaphysics* has some points of overlap with the works making up the *Organon* but is not traditionally considered part of it; additionally there are works on logic attributed, with varying degrees of plausibility, to Aristotle that were not known to the Peripatetics.

Aristotle introduced what may be called a scientific method. His demonstration method is found in *Posterior Analytics*. He provided another of the ingredients of scientific tradition: empiricism. For Aristotle, universal truths can be known from particular things via induction. To some extent then, Aristotle reconciles abstract thought with observation, although it would be a mistake to imply that Aristotelian science is empirical in form. Indeed, Aristotle did not accept that knowledge acquired by induction could rightly be counted as scientific knowledge. Nevertheless, induction was for him a necessary preliminary to the main business of scientific enquiry, providing the primary premises required for scientific demonstrations.

Aristotle largely ignored inductive reasoning in his treatment of scientific enquiry. To make it clear why this is so, consider this statement in the *Posterior Analytics*:

We suppose ourselves to possess unqualified scientific knowledge of a thing, as opposed to knowing it in the accidental way in which the sophist knows, when we think that we know the cause on which the fact depends, as the cause of that fact and of no other, and, further, that the fact could not be other than it is.

It was therefore the work of the philosopher to demonstrate universal truths and to discover their causes. While induction was sufficient for discovering universals by generalization, it did not succeed in identifying causes. For this task Aristotle used the tool of deductive reasoning in the form of syllogisms. Using the syllogism, scientists could infer new universal truths from those already established.

Aristotle developed a complete normative approach to scientific inquiry involving the syllogism, which he discusses at length in his *Posterior Analytics*. A difficulty with this scheme lay in showing that derived truths have solid primary premises. Aristotle would not allow that demonstrations could be circular (supporting the conclusion by the premises, and the premises by the conclusion). Nor would he allow an infinite number of middle terms between the primary premises and the conclusion. This leads to the question of how the primary premises are found or developed, and as mentioned above, Aristotle allowed that induction would be required for this task.

Towards the end of the *Posterior Analytics*, Aristotle discusses knowledge imparted by induction.

Thus it is clear that we must get to know the primary premises by induction; for the method by which even sense-perception implants the universal is inductive. [...] it follows that there will be no scientific knowledge of the primary premises, and since except intuition nothing can be truer than scientific knowledge, it will be intuition that apprehends the primary premises. [...] If, therefore, it is the only other kind of true thinking except scientific knowing, intuition will be the originative source of scientific knowledge.

The account leaves room for doubt regarding the nature and extent of Aristotle's empiricism. In particular, it seems that Aristotle considers sense-perception only as a vehicle for knowledge through intuition. He restricted his investigations in natural history to their natural settings, such as at the Pyrrha lagoon, now called Kalloni, at Lesbos. Aristotle and Theophrastus together formulated the new science of biology, inductively, case by case, for two years before Aristotle was called to tutor Alexander. Aristotle performed no modern-style experiments in the form in which they appear in today's physics and chemistry laboratories. Induction is not afforded the status of scientific reasoning, and so it is left to intuition to provide a solid foundation for Aristotle's science. With that said, Aristotle brings us somewhat closer an empirical science than his predecessors.

Epicurus

In his work Κανών ('canon', a straight edge or ruler, thus any type of measure or standard, referred to as 'canonic'), Epicurus laid out his first rule for inquiry in physics: 'that the *first concepts be seen*, and that they *not require demonstration* '.

His second rule for inquiry was that prior to an investigation, *we are to have self-evident concepts*, so that we might infer [ἕχωμενοἷςσημειωσόμεθα] both what is expected [τὸπροσμένον], and also what is non-apparent [τὸἄδηλον].

Epicurus applies his method of inference (the use of observations as signs, Asmis' summary, p. 333: *the method of using the phenomena as signs (σημεῖα) of what is unobserved*) immediately to the atomic theory of Democritus. In Aristotle's *Prior Analytics*, Aristotle himself employs the use of signs. But Epicurus presented his 'canonic' as rival to Aristotle's logic. See: Lucretius (c. 99 BCE – c. 55 BCE) *De rerum natura* (*On the nature of things*) a didactic poem explaining Epicurus' philosophy and physics.

Emergence of inductive experimental method

During the Middle Ages issues of what is now termed science began to be addressed. There was greater emphasis on combining theory with practice in the Islamic world than there had been in Classical times, and it was common for those studying the sciences to be artisans as well, something that had been "considered an aberration in the ancient world." Islamic experts in the sciences were often expert instrument makers who enhanced their powers of observation and calculation with them. Starting in the early ninth century, early Muslim scientists such al-Kindi (801–873) and the authors writing under the name of Jābir ibn Hayyān (writings dated to c. 850–950) started to put a greater emphasis on the use of experiment as a source of knowledge. Several scientific methods thus emerged from the medieval Muslim world by the early 11th century, all of which emphasized experimentation as well as quantification to varying degrees.

Ibn al-Haytham

The Arab physicist Ibn al-Haytham (Alhazen) used experimentation to obtain the results in his *Book of Optics* (1021). He combined observations, experiments and rational arguments to support his intromission theory of vision, in which rays of light are emitted from objects rather than from the eyes. He used similar arguments to show that the ancient emission theory of vision supported by Ptolemy and Euclid (in which the eyes emit the rays of light used for seeing), and the ancient intromission theory supported by Aristotle (where objects emit physical particles to the eyes), were both wrong.

Experimental evidence supported most of the propositions in his *Book of Optics* and grounded his theories of vision, light and colour, as well as his research in catoptrics and dioptrics. His legacy was elaborated through the 'reforming' of his *Optics* by Kamal al-Din al-Farisi (d. c. 1320) in the latter's *Kitab Tanqih al-Manazir* (*The Revision of* [Ibn al-Haytham's] *Optics*).

Alhazen viewed his scientific studies as a search for truth: "Truth is sought for its own sake. And those who are engaged upon the quest for anything for its own sake are not interested in other things. Finding the truth is difficult, and the road to it is rough. ...

Alhazen's work included the conjecture that "Light travels through transparent bodies in straight lines only", which he was able to corroborate only after years of effort. He stated, "[This] is clearly observed in the lights which enter into dark rooms through holes. ... the entering light will be clearly observable in the dust which fills the air." He also demonstrated the conjecture by placing a straight stick or a taut thread next to the light beam.

Ibn al-Haytham also employed scientific skepticism and emphasized the role of empiricism. He also explained the role of induction in syllogism, and criticized Aristotle for his lack of contribution to the method of induction, which Ibn al-Haytham regarded as superior to syllogism, and he considered induction to be the basic requirement for true scientific research.

Something like Occam's razor is also present in the *Book of Optics*. For example, after demonstrating that light is generated by luminous objects and emitted or reflected into the eyes, he states that therefore "the extramission of [visual] rays is superfluous and useless." He may also have been the first scientist to adopt a form of positivism in his approach. He wrote that "we do not go beyond experience, and we cannot be content to use pure concepts in investigating natural phenomena", and that the understanding of these cannot be acquired without mathematics. After assuming that light is a material substance, he does not further discuss its nature but confines his investigations to the diffusion and propagation of light. The only properties of light he takes into account are those treatable by geometry and verifiable by experiment.

Al-Biruni

The Persian scientist Abū Rayhān al-Bīrūnī introduced early scientific methods for several different fields of inquiry during the 1020s and 1030s. For example, in his treatise on mineralogy, *Kitab al-Jawahir* (*Book of Precious Stones*), al-Biruni is "the most exact of experimental scientists", while in the introduction to his study of India, he declares that "to execute our project, it has not been possible to follow the geometric method" and thus became one of the pioneers of comparative sociology in insisting on field experience and information. He also developed an early experimental method for mechanics.

Al-Biruni's methods resembled the modern scientific method, particularly in his emphasis on repeated experimentation. Biruni was concerned with how to conceptualize and prevent both systematic errors and observational biases, such as "errors caused by the use of small instruments and errors made by human observers." He argued that if instruments produce errors because of their imperfections or idiosyncratic qualities, then multiple observations must be taken, analyzed qualitatively, and on this basis, arrive at a "common-sense single value for the constant sought", whether an arithmetic mean or a "reliable estimate." In his scientific method, "universals came out of practical, experimental work" and "theories are formulated after discoveries", as with inductivism.

Ibn Sina (Avicenna)

In the *On Demonstration* section of *The Book of Healing* (1027), the Persian philosopher and scientist Avicenna (Ibn Sina) discussed philosophy of science and described an early scientific method of inquiry. He discussed Aristotle's *Posterior Analytics* and significantly diverged from it on several points. Avicenna discussed the issue of a proper procedure for scientific inquiry and the question of "How does one acquire the first principles of a science?" He asked how a scientist might find "the initial axioms or hypotheses of a deductive science without inferring them from some more basic premises?" He explained that the ideal situation is when one grasps that a "relation holds between the terms, which would allow for absolute, universal certainty." Avicenna added two further methods for finding a first principle: the ancient Aristotelian method of induction (*istiqra*), and the more recent method of examination and experimentation (*tajriba*). Avicenna criticized Aristotelian induction, arguing that "it does not lead to the absolute, universal, and certain premises that it purports to provide." In its place, he advocated "a method of experimentation as a means for scientific inquiry."

Earlier, in *The Canon of Medicine* (1025), Avicenna was also the first to describe what is essentially methods of agreement, difference and concomitant variation which are critical to inductive logic and the scientific method. However, unlike his contemporary al-Biruni's scientific method, in which "universals came out of practical, experimental work" and "theories are formulated after discoveries", Avicenna developed a scientific procedure in which "general and universal questions came first and led to experimental work." Due to the differences between their methods, al-Biruni referred to himself as a mathematical scientist and to Avicenna as a philosopher, during a debate between the two scholars.

Robert Grosseteste

During the European Renaissance of the 12th century, ideas on scientific methodology, including Aristotle's empiricism and the experimental approaches of Alhazen and Avicenna, were introduced to medieval Europe via Latin translations of Arabic and Greek texts and commentaries. Robert Grosseteste's commentary on the *Posterior Analytics* places Grosseteste among the first scholastic thinkers in Europe to understand Aristotle's vision of the dual nature of scientific reasoning. Concluding from particular observations into a universal law, and then back again, from universal laws to prediction of particulars. Grosseteste called this "resolution and composition". Further, Grosseteste said that both paths should be verified through experimentation to verify the principles.

Roger Bacon

Roger Bacon was inspired by the writings of Grosseteste. In his account of a method, Bacon described a repeating cycle of *observation*, *hypothesis*, *experimentation*, and the need for independent *verification*. He recorded the way he had conducted his experiments in precise detail, perhaps with the idea that others could reproduce and independently test his results.

About 1256 he joined the Franciscan Order and became subject to the Franciscan statute forbidding Friars from publishing books or pamphlets without specific approval. After the accession of Pope Clement IV in 1265, the Pope granted Bacon a special commission to write to him on scientific matters. In eighteen months he completed three large treatises, the *Opus Majus*, *Opus Minus*, and *Opus Tertium* which he sent to the Pope. William Whewell has called *Opus Majus* at once the Encyclopaedia and Organon of the 13th century.

- Part I (pp. 1–22) treats of the four causes of error: authority, custom, the opinion of the unskilled many, and the concealment of real ignorance by a pretense of knowledge.
- Part VI (pp. 445–477) treats of experimental science, *domina omnium scientiarum*. There are two methods of knowledge: the one by argument, the other by experience. Mere argument is never sufficient; it may decide a question, but gives no satisfaction or certainty to the mind, which can only be convinced by immediate inspection or intuition, which is what experience gives.
- Experimental science, which in the *Opus Tertium* (p. 46) is distinguished from the speculative sciences and the operative arts, is said to have three great prerogatives over all sciences:
- It verifies their conclusions by direct experiment;
- It discovers truths which they could never reach;

- It investigates the secrets of nature, and opens to us a knowledge of past and future.
- Roger Bacon illustrated his method by an investigation into the nature and cause of the rainbow, as a specimen of inductive research.

Renaissance humanism and medicine

Aristotle's ideas became a framework for critical debate beginning with absorption of the Aristotelian texts into the university curriculum in the first half of the 13th century. Contributing to this was the success of medieval theologians in reconciling Aristotelian philosophy with Christian theology. Within the sciences, medieval philosophers were not afraid of disagreeing with Aristotle on many specific issues, although their disagreements were stated within the language of Aristotelian philosophy. All medieval natural philosophers were Aristotelians, but "Aristotelianism" had become a somewhat broad and flexible concept. With the end of Middle Ages, the Renaissance rejection of medieval traditions coupled with an extreme reverence for classical sources led to a recovery of other ancient philosophical traditions, especially the teachings of Plato. By the 17th century, those who clung dogmatically to Aristotle's teachings were faced with several competing approaches to nature.

The discovery of the Americas at the close of the 15th century showed the scholars of Europe that new discoveries could be found outside of the authoritative works of Aristotle, Pliny, Galen, and other ancient writers.

Galen of Pergamon (129 – c. 200 AD) had studied with four schools in antiquity — Platonists, Aristotelians, Stoics, and Epicureans, and at Alexandria, the center of medicine at the time. In his *Methodus Medendi*, Galen had synthesized the empirical and dogmatic schools of medicine into his own method, which was preserved by Arab scholars. After the translations from Arabic were critically scrutinized, a backlash occurred and demand arose in Europe for translations of Galen's medical text from the original Greek. Galen's method became very popular in Europe. Thomas Linacre, the teacher of Erasmus, thereupon translated *Methodus Medendi* from Greek into Latin for a larger audience in 1519. Limbrick 1988 notes that 630 editions, translations, and commentaries on Galen were produced in Europe in the 16th century, eventually eclipsing Arabic medicine there, and peaking in 1560, at the time of the scientific revolution.

By the late 15th century, the physician-scholar Niccolò Leoniceno was finding errors in Pliny's *Natural History*. As a physician, Leoniceno was concerned about these botanical errors propagating to the materia medica on which medicines were based. To counter this, a botanical garden was established at Orto botanico di Padova, University of Padua (in use for teaching by 1546), in order that medical students might have empirical access to the plants of a pharmacopia. Other Renaissance teaching gardens were established, notably by the physician Leonhart Fuchs, one of the founders of botany.

The first published work devoted to the concept of method is Jodocus Willichius, *De methodo omnium artium et disciplinarum informanda opusculum* (1550).

Skepticism as a basis for understanding

In 1562 "Outlines of Pyrrhonism" by Sextus Empiricus (c. 160-210 AD) appeared in print and in Latin, quickly placing the arguments of classical skepticism in the European mainstream. Skepticism either denies or strongly doubts (depending on the school) the possibility of certain knowledge. Descartes' famous "Cogito" argument is an attempt to overcome skepticism and reestablish a foundation for certainty but other thinkers responded by revising what the search for knowledge, particularly physical knowledge, might be.

The first of these, philosopher and physician Francisco Sanches, was led by his medical training at Rome, 1571–73, to search for a true method of knowing (*modus sciendi*), as nothing clear can be known by the methods of Aristotle and his followers — for example, 1) syllogism fails upon circular reasoning; 2) Aristotle's modal logic was not stated clearly enough for use in medieval times, and remains a research problem to this day. Following the physician Galen's *method of medicine*, Sanches lists the methods of judgement and experience, which are faulty in the wrong hands, and we are left with the bleak statement *That Nothing is Known* (1581, in Latin *Quod Nihil Scitur*). This challenge was taken up by René Descartes in the next generation (1637), but at the least, Sanches warns us that we ought to refrain from the methods, summaries, and commentaries on Aristotle, if we seek scientific knowledge. In this, he is echoed by Francis Bacon who was influenced by another prominent exponent of skepticism, Montaigne; Sanches cites the humanist Juan Luis Vives who sought a better educational system, as well as a statement of human rights as a pathway for improvement of the lot of the poor.

"Sanches develops his scepticism by means of an intellectual critique of Aristotelianism, rather than by an appeal to the history of human stupidity and the variety and contrariety of previous theories." —Popkin 1979, p. 37, as cited by Sanches, Limbrick & Thomson 1988, pp. 24–5

"To work, then; and if you know something, then teach me; I shall be extremely grateful to you. In the meantime, as I prepare to examine *Things*, I shall raise the question anything is *known*, and if so, how, in the introductory passages of another book, a book in which I will expound, as far as human frailty allows, the *method of knowing*. Farewell.

WHAT IS TAUGHT HAS NO MORE STRENGTH THAN IT DERIVES FROM HIM WHO IS TAUGHT.

WHAT?" —Francisco Sanches (1581) *Quod Nihil Scitur* p. 100

Francis Bacon's eliminative induction

"If a man will begin with certainties, he shall end in doubts; but if he will be content to begin with doubts, he shall end in certainties." —Francis Bacon (1605) *The Advancement of Learning*, Book 1, v, 8

Francis Bacon (1561–1626) entered Trinity College, Cambridge in April 1573, where he applied himself diligently to the several sciences as then taught, and came to the conclusion that the methods employed and the results attained were alike erroneous; he learned to despise the current Aristotelian philosophy. He believed philosophy must be taught its true purpose, and for this purpose a new method must be devised. With this conception in his mind, Bacon left the university.

Bacon attempted to describe a rational procedure for establishing causation between phenomena based on induction. Bacon's induction was, however, radically different than that employed by the Aristotelians. As Bacon put it,

[A]nother form of induction must be devised than has hitherto been employed, and it must be used for proving and discovering not first principles (as they are called) only, but also the lesser axioms, and the middle, and indeed all. For the induction which proceeds by simple enumeration is childish. — *Novum Organum* section CV

Bacon's method relied on experimental *histories* to eliminate alternative theories. Bacon explains how his method is applied in his *Novum Organum* (published 1620). In an example he gives on the examination of the nature of heat, Bacon creates two tables, the first of which he names "Table of Essence and Presence", enumerating the many various circumstances under which we find heat. In the other table, labelled "Table of Deviation, or of Absence in Proximity", he lists circumstances which bear resemblance to those of the first table except for the absence of heat. From an analysis of what he calls the *natures* (light emitting, heavy, colored, etc.) of the items in these lists we are brought to conclusions about the *form nature*, or cause, of heat. Those natures which are always present in the first table, but never in the second are deemed to be the cause of heat.

The role experimentation played in this process was twofold. The most laborious job of the scientist would be to gather the facts, or 'histories', required to create the tables of presence and absence. Such histories would document a mixture of common knowledge and experimental results. Secondly, *experiments of light*, or, as we might say, crucial experiments would be needed to resolve any remaining ambiguities over causes.

Bacon showed an uncompromising commitment to experimentation. Despite this, he did not make any great scientific discoveries during his lifetime. This may be because he was not the most able experimenter. It may also be because hypothesising plays only a small role in Bacon's method compared to modern science. Hypotheses, in Bacon's method, are supposed to emerge during the process of investigation, with the help of mathematics and logic. Bacon gave a substantial but secondary role to mathematics *"which ought only to give definiteness to natural philosophy, not to generate or give it birth"* (*Novum Organum XCVI*). An over-emphasis on axiomatic reasoning had rendered previous non-empirical philosophy impotent, in Bacon's view, which was expressed in his *Novum Organum*:

XIX. There are and can be only two ways of searching into and discovering truth. The one flies from the senses and particulars to the most general axioms, and from these principles, the truth of which it takes for settled and immoveable, proceeds to judgment and to the discovery of middle axioms. And this way is now in fashion. The other derives axioms from the senses and particulars, rising by a gradual and unbroken ascent, so that it arrives at the most general axioms last of all. This is the true way, but as yet untried.

In Bacon's utopian novel, *The New Atlantis*, the ultimate role is given for inductive reasoning:

Lastly, we have three that raise the former discoveries by experiments into greater observations, axioms, and aphorisms. These we call interpreters of nature.

Descartes

In 1619, René Descartes began writing his first major treatise on proper scientific and philosophical thinking, the unfinished *Rules for the Direction of the Mind*. His aim was to create a complete science that he hoped would overthrow the Aristotelian system and establish himself as the sole architect of a new system of guiding principles for scientific research.

This work was continued and clarified in his 1637 treatise, *Discourse on Method*, and in his 1641 *Meditations*. Descartes describes the intriguing and disciplined thought experiments he used to arrive at the idea we instantly associate with him: *I think therefore I am.*

From this foundational thought, Descartes finds proof of the existence of a God who, possessing all possible perfections, will not deceive him provided he resolves "[...] never to accept anything for true which I did not clearly know to be such; that is to say, carefully to avoid precipitancy and prejudice, and to comprise nothing more in my judgment than what was presented to my mind so clearly and distinctly as to exclude all ground of methodic doubt."

This rule allowed Descartes to progress beyond his own thoughts and judge that there exist extended bodies outside of his own thoughts. Descartes published seven sets of objections to the *Meditations* from various sources along with his replies to them. Despite his apparent departure from the Aristotelian system, a number of his critics felt that Descartes had done little more than replace the primary premises of Aristotle with those of his own. Descartes says as much himself in a letter written in 1647 to the translator of Principles of Philosophy,

a perfect knowledge [...] must necessarily be deduced from first causes [...] we must try to deduce from these principles knowledge of the things which depend on them, that there be nothing in the whole chain of deductions deriving from them that is not perfectly manifest.

And again, some years earlier, speaking of Galileo's physics in a letter to his friend and critic Mersenne from 1638, without having considered the first causes of nature, [Galileo] has merely looked for the explanations of a few particular effects, and he has thereby built without foundations.

Whereas Aristotle purported to arrive at his first principles by induction, Descartes believed he could obtain them using reason only. In this sense, he was a Platonist, as he believed in the innate ideas, as opposed to Aristotle's blank slate (*tabula rasa*), and stated that the seeds of science are inside us.

Unlike Bacon, Descartes successfully applied his own ideas in practice. He made significant contributions to science, in particular in aberration-corrected optics. His work in analytic geometry was a necessary precedent to differential calculus and instrumental in bringing mathematical analysis to bear on scientific matters.

Galileo Galilei

During the period of religious conservatism brought about by the Reformation and Counter-Reformation, Galileo Galilei unveiled his new science of motion. Neither the contents of Galileo's science, nor the methods of study he selected were in keeping with Aristotelian teachings. Whereas Aristotle thought that a science should be demonstrated from first principles, Galileo had used experiments as a research tool. Galileo nevertheless presented his treatise in the form of mathematical demonstrations without reference to experimental results. It is important to understand that this in itself was a bold and innovative step in terms of scientific method. The usefulness of mathematics in obtaining scientific results was far from obvious. This is because mathematics did not lend itself to the primary pursuit of Aristotelian science: the discovery of causes.

Whether it is because Galileo was realistic about the acceptability of presenting experimental results as evidence or because he himself had doubts about the epistemological status of experimental findings is not known. Nevertheless, it is not in his Latin treatise on motion that we find reference to experiments, but in his supplementary dialogues written in the Italian vernacular. In these dialogues experimental results are given, although Galileo may have found them inadequate for persuading his audience. Thought experiments showing logical contradictions in Aristotelian thinking, presented in the skilled rhetoric of Galileo's dialogue were further enticements for the reader.

As an example, in the dramatic dialogue titled *Third Day* from his *Two New Sciences*, Galileo has the characters of the dialogue discuss an experiment involving two free falling objects of differing weight. An outline of the Aristotelian view is offered by the character Simplicio. For this experiment he expects that "a body which is ten times as heavy as another will move ten times as rapidly as the other". The character Salviati, representing Galileo's persona in the dialogue, replies by voicing his doubt that Aristotle ever attempted the experiment. Salviati then asks the two other characters of the dialogue to consider a thought experiment whereby two stones of differing weights are tied together before being released. Following Aristotle, Salviati reasons that "the more rapid one will be partly retarded by the slower, and the slower will be somewhat hastened by the swifter". But this leads to a contradiction, since the two stones together make a heavier object than either stone apart, the heavier object should in fact fall with a speed greater than that of either stone. From this contradiction, Salviati concludes that Aristotle must, in fact, be wrong and the objects will fall at the same speed regardless of their weight, a conclusion that is borne out by experiment.

In his 1991 survey of developments in the modern accumulation of knowledge such as this Charles Van Doren considers that the Copernican Revolution really is the Galilean Cartesian (René Descartes) or simply the Galilean revolution on account of the courage and depth of change brought about by the work of Galileo.

Isaac Newton

Both Bacon and Descartes wanted to provide a firm foundation for scientific thought that avoided the deceptions of the mind and senses. Bacon envisaged that foundation as essentially empirical, whereas Descartes provides a metaphysical foundation for knowledge. If there were any doubts about the direction in which scientific method would develop, they were set to rest by the success of Isaac Newton. Implicitly rejecting Descartes' emphasis on rationalism in favor of Bacon's empirical approach, he outlines his four "rules of reasoning" in the *Principia*,

- We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances.
- Therefore to the same natural effects we must, as far as possible, assign the same causes.
- The qualities of bodies, which admit neither intension nor remission of degrees, and which are found to belong to all bodies within the reach of our experiments, are to be esteemed the universal qualities of all bodies whatsoever.
- In experimental philosophy we are to look upon propositions collected by general induction from phænomena as accurately or very nearly true, notwithstanding any contrary hypotheses that may be imagined, until such time as other phænomena occur, by which they may either be made more accurate, or liable to exceptions.

But Newton also left an admonition about a theory of everything:

To explain all nature is too difficult a task for any one man or even for any one age. 'Tis much better to do a little with certainty, and leave the rest for others that come after you, than to explain all things.

Newton's work became a model that other sciences sought to emulate, and his inductive approach formed the basis for much of natural philosophy through the 18th and early 19th centuries. Some methods of reasoning were later systematized by Mill's Methods (or Mill's canon), which are five explicit statements of what can be discarded and what can be kept while building a hypothesis. George Boole and William Stanley Jevons also wrote on the principles of reasoning.

Integrating deductive and inductive method

Attempts to systematize a scientific method were confronted in the mid-18th century by the problem of induction, a positivist logic formulation which, in short, asserts that nothing can be known with certainty except what is actually observed. David Hume took empiricism to the skeptical extreme; among his positions was that there is no logical necessity that the future should resemble the past, thus we are unable to justify inductive reasoning itself by appealing to its past success. Hume's arguments, of course, came on the heels of many, many centuries of excessive speculation upon excessive speculation not grounded in empirical observation and testing. Many of Hume's radically skeptical arguments were argued against, but not resolutely refuted, by Immanuel Kant's *Critique of Pure Reason* in the late 18th century. Hume's arguments continue to hold a strong lingering influence and certainly on the consciousness of the educated classes for the better part of the 19th century when the argument at the time became the focus on whether or not the inductive method was valid.

Hans Christian Ørsted, (Ørsted is the Danish spelling; *Oersted* in other languages) (1777–1851) was heavily influenced by Kant, in particular, Kant's *Metaphysische Anfangsgründe der Naturwissenschaft* (*Metaphysical Foundations of Natural Science*). The following sections on Ørsted encapsulate our current, common view of scientific method. His work appeared in Danish, most accessibly in public lectures, which he translated into German, French, English, and occasionally Latin. But some of his views go beyond Kant:

- "In order to achieve completeness in our knowledge of nature, we must start from two extremes, from experience and from the intellect itself. ... The former method must conclude with natural laws, which it has abstracted from experience, while the latter must begin with principles, and gradually, as it develops more and more, it becomes ever more detailed. Of course, I speak here about the method as manifested in the process of the human intellect itself, not as found in textbooks, where the laws of nature which have been abstracted from the consequent experiences are placed first because they

> are required to explain the experiences. When the empiricist in his regression towards general laws of nature meets the metaphysician in his progression, science will reach its perfection."

Ørsted's "First Introduction to General Physics" (1811) exemplified the steps of observation, hypothesis, deduction and experiment. In 1805, based on his researches on electromagnetism Ørsted came to believe that electricity is propagated by undulatory action (i.e., fluctuation). By 1820, he felt confident enough in his beliefs that he resolved to demonstrate them in a public lecture, and in fact observed a small magnetic effect from a galvanic circuit (i.e., voltaic circuit), *without rehearsal*;

In 1831 John Herschel (1792–1871) published *A Preliminary Discourse on the study of Natural Philosophy*, setting out the principles of science. Measuring and comparing observations was to be used to find generalisations in "empirical laws", which described regularities in phenomena, then natural philosophers were to work towards the higher aim of finding a universal "law of nature" which explained the causes and effects producing such regularities. An explanatory hypothesis was to be found by evaluating true causes (Newton's "vera causae") derived from experience, for example evidence of past climate change could be due to changes in the shape of continents, or to changes in Earth's orbit. Possible causes could be inferred by analogy to known causes of similar phenomena. It was essential to evaluate the importance of a hypothesis; "our next step in the verification of an induction must, therefore, consist in extending its application to cases not originally contemplated; in studiously varying the circumstances under which our causes act, with a view to ascertain whether their effect is general; and in pushing the application of our laws to extreme cases."

William Whewell (1794–1866) regarded his *History of the Inductive Sciences, from the Earliest to the Present Time* (1837) to be an introduction to the *Philosophy of the Inductive Sciences* (1840) which analyzes the method exemplified in the formation of ideas. Whewell attempts to follow Bacon's plan for discovery of an effectual art of discovery. He named the hypothetico-deductive method (which *Encyclopædia Britannica* credits to Newton); Whewell also coined the term *scientist*. Whewell examines ideas and attempts to construct science by uniting ideas to facts. He analyses induction into three steps:

- the selection of the fundamental idea, such as space, number, cause, or likeness
- a more special modification of those ideas, such as a circle, a uniform force, etc.
- the determination of magnitudes

Upon these follow special techniques applicable for quantity, such as the method of least squares, curves, means, and special methods depending on resemblance (such as pattern matching, the method of gradation, and the method of natural classification (such as cladistics). But no art of discovery, such as Bacon anticipated, follows, for "invention, sagacity, genius" are needed at every step. Whewell's sophisticated concept of science had similarities to that shown by Herschel, and he considered that a good hypothesis should connect fields that had previously been thought unrelated, a process he called consilience. However, where Herschel held that the origin of new biological species would be found in a natural rather than a miraculous process, Whewell opposed this and considered that no natural cause had been shown for adaptation so an unknown divine cause was appropriate.

John Stuart Mill (1806–1873) was stimulated to publish *A System of Logic* (1843) upon reading Whewell's *History of the Inductive Sciences*. Mill may be regarded as the final exponent of the empirical school of philosophy begun by John Locke, whose fundamental characteristic is the duty incumbent upon all thinkers to investigate for themselves rather than to accept the authority of others. Knowledge must be based on experience.

In the mid-19th century Claude Bernard was also influential, especially in bringing the scientific method to medicine. In his discourse on scientific method, *An Introduction to the Study of Experimental Medicine* (1865), he described what makes a scientific theory good and what makes a scientist a true discoverer. Unlike many scientific writers of his time, Bernard wrote about his own experiments and thoughts, and used the first person.

William Stanley Jevons' *The Principles of Science: a treatise on logic and scientific method* (1873, 1877) Chapter XII "The Inductive or Inverse Method", Summary of the Theory of Inductive Inference, states "Thus there are but three steps in the process of induction :-

- Framing some hypothesis as to the character of the general law.
- Deducing some consequences of that law.

- Observing whether the consequences agree with the particular tasks under consideration."

Jevons then frames those steps in terms of probability, which he then applied to economic laws. Ernest Nagel notes that Jevons and Whewell were not the first writers to argue for the centrality of the hypothetico-deductive method in the logic of science.

Charles Sanders Peirce

In the late 19th century, Charles Sanders Peirce proposed a schema that would turn out to have considerable influence in the further development of scientific method generally. Peirce's work quickly accelerated the progress on several fronts. Firstly, speaking in broader context in "How to Make Our Ideas Clear" (1878), Peirce outlined an objectively verifiable method to test the truth of putative knowledge on a way that goes beyond mere foundational alternatives, focusing upon both Deduction and Induction. He thus placed induction and deduction in a complementary rather than competitive context (the latter of which had been the primary trend at least since David Hume a century before). Secondly, and of more direct importance to scientific method, Peirce put forth the basic schema for hypothesis-testing that continues to prevail today. Extracting the theory of inquiry from its raw materials in classical logic, he refined it in parallel with the early development of symbolic logic to address the then-current problems in scientific reasoning. Peirce examined and articulated the three fundamental modes of reasoning that play a role in scientific inquiry today, the processes that are currently known as abductive, deductive, and inductive inference. Thirdly, he played a major role in the progress of symbolic logic itself – indeed this was his primary specialty.

Charles S. Peirce was also a pioneer in statistics. Peirce held that science achieves statistical probabilities, not certainties, and that chance, a veering from law, is very real. He assigned probability to an argument's conclusion rather than to a proposition, event, etc., as such. Most of his statistical writings promote the frequency interpretation of probability (objective ratios of cases), and many of his writings express skepticism about (and criticize the use of) probability when such models are not based on objective randomization. Though Peirce was largely a frequentist, his possible world semantics introduced the "propensity" theory of probability. Peirce (sometimes with Jastrow) investigated the probability judgments of experimental subjects, pioneering decision analysis.

Peirce was one of the founders of statistics. He formulated modern statistics in "Illustrations of the Logic of Science" (1877–1878) and "A Theory of Probable Inference" (1883). With a repeated measures design, he introduced blinded, controlled randomized experiments (before Fisher). He invented an optimal design for experiments on gravity, in which he "corrected the means". He used logistic regression, correlation, and smoothing, and improved the treatment of outliers. He introduced terms "confidence" and "likelihood" (before Neyman and Fisher). (See the historical books of Stephen Stigler.) Many of Peirce's ideas were later popularized and developed by Ronald A. Fisher, Jerzy Neyman, Frank P. Ramsey, Bruno de Finetti, and Karl Popper.

Modern perspectives

Karl Popper (1902–1994) is generally credited with providing major improvements in the understanding of the scientific method in the mid-to-late 20th century. In 1934 Popper published *The Logic of Scientific Discovery*, which repudiated the by then traditional observationalist-inductivist account of the scientific method. He advocated empirical falsifiability as the criterion for distinguishing scientific work from non-science. According to Popper, scientific theory should make predictions (preferably predictions not made by a competing theory) which can be tested and the theory rejected if these predictions are shown not to be correct. Following Peirce and others, he argued that science would best progress using deductive reasoning as its primary emphasis, known as critical rationalism. His astute formulations of logical procedure helped to rein in the excessive use of inductive speculation upon inductive speculation, and also helped to strengthen the conceptual foundations for today's peer review procedures.

Ludwik Fleck, a Polish epidemiologist who was contemporary with Karl Popper but who influenced Kuhn and others with his *Genesis and Development of a Scientific Fact* (in German 1935, English 1979). Before Fleck, scientific fact was thought to spring fully formed (in the view of Max Jammer, for example), when a gestation period is now recognized to be essential before acceptance of a phenomenon as fact.

Critics of Popper, chiefly Thomas Kuhn, Paul Feyerabend and Imre Lakatos, rejected the idea that there exists a *single* method that applies to all science and could account for its progress. In 1962 Kuhn published the influential book *The*

Structure of Scientific Revolutions which suggested that scientists worked within a series of paradigms, and argued there was little evidence of scientists actually following a falsificationist methodology. Kuhn quoted Max Planck who had said in his autobiography, "a new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it."

These debates clearly show that there is no universal agreement as to what constitutes *the* "scientific method". There remain, nonetheless, certain core principles that are the foundation of scientific inquiry today.

Mention of the topic

In *Quod Nihil Scitur* (1581), Francisco Sanches refers to another book title, *De modo sciendi* (on the method of knowing). This work appeared in Spanish as *Método universal de las ciencias*.

In 1833 Robert and William Chambers published their 'Chambers's information for the people'. Under the rubric 'Logic' we find a description of investigation that is familiar as scientific method,

Investigation, or the art of inquiring into the nature of causes and their operation, is a leading characteristic of reason [...] Investigation implies three things – Observation, Hypothesis, and Experiment [...] The first step in the process, it will be perceived, is to observe...

In 1885, the words "Scientific method" appear together with a description of the method in Francis Ellingwood Abbot's 'Scientific Theism',

Now all the established truths which are formulated in the multifarious propositions of science have been won by the use of Scientific Method. This method consists in essentially three distinct steps (1) observation and experiment, (2) hypothesis, (3) verification by fresh observation and experiment.

The Eleventh Edition of *Encyclopædia Britannica* did not include an article on scientific method; the Thirteenth Edition listed scientific management, but not method. By the Fifteenth Edition, a 1-inch article in the *Micropædia* of Britannica was part of the 1975 printing, while a fuller treatment (extending across multiple articles, and accessible mostly via the index volumes of Britannica) was available in later printings.

Current issues

In the past few centuries, some statistical methods have been developed, for reasoning in the face of uncertainty, as an outgrowth of methods for eliminating error. This was an echo of the program of Francis Bacon's *Novum Organum* of 1620. Bayesian inference acknowledges one's ability to alter one's beliefs in the face of evidence. This has been called belief revision, or defeasible reasoning: the models in play during the phases of scientific method can be reviewed, revisited and revised, in the light of further evidence. This arose from the work of Frank P. Ramsey (1903–1930), of John Maynard

Keynes (1883–1946), and earlier, of William Stanley Jevons (1835–1882) in economics.

Science and pseudoscience

The question of how science operates and therefore how to distinguish genuine science from pseudoscience has importance well beyond scientific circles or the academic community. In the judicial system and in public policy controversies, for example, a study's deviation from *accepted scientific practice* is grounds for rejecting it as junk science or pseudoscience. However, the high public perception of science means that pseudoscience is widespread. An advertisement in which an actor wears a white coat and product ingredients are given Greek or Latin sounding names is intended to give the impression of scientific endorsement. Richard Feynman has likened pseudoscience to cargo cults in which many of the external forms are followed, but the underlying basis is missing: that is, fringe or alternative theories often present themselves with a pseudoscientific appearance to gain acceptance.

Chapter 3

Sociology of the History of Science

The **sociology of the history of science**—related to sociology and philosophy of science, as well as the entire field of science studies—has in the 20th century been occupied with the question of large-scale patterns and trends in the development of science, and asking questions about how science "works" both in a philosophical and practical sense.

Science as a social enterprise

Science as a social enterprise has been developing exponentially for the past few centuries. In antiquity, the few people who were able to engage in natural inquiry were either wealthy themselves, had rich benefactors, or had the support of a religious community. Today, scientific research has tremendous government support and also ongoing support from the private sector.

Available methods of communication have improved tremendously over time. Instead of waiting months or years for a hand-copied letter to arrive, today scientific communication can be practically instantaneous. Earlier, most natural philosophers worked in relative isolation, due to the difficulty and slowness of communication. Still, there was a considerable amount of cross-fertilization between distant groups and individuals.

Nowadays, almost all modern scientists participate in a scientific community, hypothetically global in nature (though often based around a relatively few nations and institutions of stature), but also strongly segregated into different fields of study. The scientific community is important because it represents a source of established knowledge which, if used properly, ought to be more reliable than personally acquired knowledge of any given individual. The community also provides a feedback mechanism, often in the form of practices such as peer review and reproducibility. Most items of scientific content (experimental results, theoretical proposals, or literature reviews) are reported in scientific journals and are hypothetically subjected to peer scrutiny, though a number of scholarly critics from both inside and outside the scientific community have, in recent decades, began to question the effect of commercial and government investment in science on the peer review and publishing process, as well as the internal disciplinary limitations to the scientific publication process.

A major development of the Scientific Revolution was the foundation of scientific societies: Academia Secretorum Naturae (Accademia dei Segreti, the Academy of the Mysteries of Nature) can be considered the first scientific community; founded in Naples 1560 by Giambattista della Porta. The Academy had an exclusive membership rule: discovery of a new law of nature was a prerequisite for admission. It was soon shut down by Pope Paul V for alleged sorcery.

The Academia Secretorum Naturae was replaced by the Accademia dei Lincei, which was founded in Rome in 1603. The Lincei included Galileo as a member, but failed upon his condemnation in 1633. The Accademia del Cimento, Florence 1657, lasted 10 years. The Royal Society of London, 1660 to the present day, brought together a diverse collection of scientists to discuss theories, conduct experiments, and review each other's work. The Académie des Sciences was created as an institution of the government of France 1666, meeting in the King's library. The Akademie der Wissenschaften began in Berlin 1700.

Early scientific societies provided valuable functions, including a community open to and interested in empirical inquiry, and also more familiar with and more educated about the subject. In 1758, with the aid of his pupils, Lagrange established a society, which was subsequently incorporated as the Turin Academy.

Much of what is considered the modern institution of science was formed during its professionalization in the 19th century. During this time the location of scientific research shifted primarily to universities, though to some extent it also became a standard component of industry as well. In the early years of the 20th century, especially after the role of science in the first World War, governments of major industrial nations began to invest heavily in scientific research. This effort was dwarfed by the funding of scientific research undertaken by all sides in World War II, which produced such "wonder weapons" as radar, rocketry, and the atomic bomb. During the Cold War, a large amount of government resources were poured into science by the United States, USSR, and many European powers. It was during this time that DARPA funded nationwide computer networks, one of them eventually under the internet protocol. In the post-Cold War era, a decline in government funding from many countries has been met with an increase of industrial and private investment. The funding of science is a major factor in its historical and global development. So although science is hypothetically international in scope, in a practical sense it has usually centered around wherever it could find the most funding.

During the Scientific Revolution, early scientists communicated in Latin, which had been the language of academia during the Middle Ages, and which was read and written by scholars from many countries. In the mid-1600s, publications started to appear in local languages. By 1900, German, French and English were dominant. Anti-German sentiment caused by World War I and World War II and boycotts of German scientists resulted in the loss of German as a scientific language. In later decades of the 20th century, the economic dominance and scientific productivity of the United States led to the rise of English, which after the end of the Cold War has become the dominant language of scientific communication.

Political support

One of the basic requirements for a scientific community is the existence and approval of a political sponsor; in England, the Royal Society operates under the aegis of the monarchy; in the US, the National Academy of Sciences was founded by Act of the United States Congress; etc. Otherwise, when the basic elements of knowledge were being formulated, the political rulers of the respective communities could choose to arbitrarily either support or disallow the nascent scientific communities. For example, Alhazen had to feign madness to avoid execution. The polymath Shen Kuo lost political support, and could not continue his studies until he came up with discoveries that showed his worth to the political rulers. The admiral Zheng He could not continue his voyages of exploration after the emperors withdrew their support. Another famous example was the suppression of the work of Galileo, by the twentieth century, Galileo would be pardoned.

Patterns in the history of science

- One of the major occupations with those interested in the history of science is whether or not it displays certain patterns or trends, usually along the question of change between one or more scientific theories. Generally speaking, there have historically been three major models adopted in various forms within the philosophy of science.

The first major model, implicit in most early histories of science and generally a model put forward by practicing scientists themselves in their textbook literature, is associated with the criticisms of logical positivism by Karl Popper (1902–1994) from the 1930s. Popper's model of science is one in which scientific progress is achieved through a falsification of incorrect theories and the adoption instead of theories which are progressively closer to truth. In this model, scientific progress is a linear accumulation of facts, each one adding to the last. In this model, the physics of Aristotle (384 BC – 322 BC) was simply subsumed by the work of Isaac Newton (1642–1727) (classical mechanics), which itself was eclipsed by the work of Albert Einstein (1879–1955) (Relativity), and later the theory of quantum mechanics (established in 1925), each one more accurate than the last.

A major challenge to this model came from the work of the historian and philosopher Thomas Kuhn (1922–1996) in his work *The Structure of Scientific Revolutions* published in 1962. Kuhn, a former physicist, argued against the view that scientific progress was linear, and that modern scientific theories were necessarily just more accurate versions of theories of the past. Rather, Kuhn's version of scientific development consisted of dominant structures of thought and practices, which he called "paradigms", in which research went through phases of "normal" science ("puzzle solving") and "revolutionary" science (testing out new theories based on new assumptions, brought on by uncertainty and crisis in existing theories). In Kuhn's model, different paradigms represented entirely different and incommensurate assumptions about the universe. The mode was thus uncertain about whether paradigms shifted in a way which necessarily relied upon greater attainment of truth. In Kuhn's view, Aristotle's physics, Newton's classical mechanics, and Einstein's Relativity were entirely different ways to think about the world; each successive paradigm defined what questions could be asked about the world and (perhaps arbitrarily) discarded aspects of the previous paradigm which no longer seemed applicable or important. Kuhn claimed that far from merely building on the previous theory's accomplishments, each new paradigm essentially throws out the old way of looking at the universe, and comes up with its own vocabulary to describe it and its own guidelines for expanding knowledge within the new paradigm.

Kuhn's model met with much suspicion from scientists, historians, and philosophers. Some scientists felt that Kuhn went too far in divorcing scientific progress from truth; many historians felt that his argument was too codified for something as polyvariant and historically contingent as scientific change; and many philosophers felt that the argument did not go far enough. The furthest extreme of such reasoning was put forth by the philosopher Paul Feyerabend (1924–1994), who argued that there were no consistent methodologies used by all scientists at all times which allowed certain forms of inquiry to be labeled "scientific" in a way which made them different from any other form of inquiry, such as witchcraft. Feyerabend argued harshly against the notion that falsification was ever truly followed in the history of science, and noted that scientists had long undertaken practices to arbitrarily consider theories to be accurate even if they failed many sets of tests. Feyerabend argued that a pluralistic methodology should be undertaken for the investigation of knowledge, and noted that many forms of knowledge which were previously thought to be "non-scientific" were later accepted as a valid part of the scientific canon.

Many other theories of scientific change have been proposed over the years with various changes of emphasis and implications. In general, though, most float somewhere between these three models for change in scientific theory, the connection between theory and truth, and the nature of scientific progress.

The nature of scientific discovery

Individual ideas and accomplishments are among the most famous aspects of science, both internally and in larger society. Breakthrough figures like Sir Isaac Newton or Albert Einstein are often celebrated as geniuses and heroes of science. Popularizers of science, including the news media and scientific biographers, contribute to this phenomenon. But many scientific historians emphasize the collective aspects of scientific discovery, and de-emphasize the importance of the "Eureka!" moment.

A detailed look at the history of science often reveals that the minds of great thinkers were primed with the results of previous efforts, and often arrive on the scene to find a crisis of one kind or another. For example, Einstein did not consider the physics of motion and gravitation in isolation. His major accomplishments solved a problem which had come to a head in the field only in recent years — empirical data showing that the speed of light was inexplicably constant, no matter the apparent speed of the observer. (See Michelson–Morley experiment.) Without this information, it is very unlikely that Einstein would have conceived of anything like relativity.

The question of who should get credit for any given discovery is often a source of some controversy. There are many priority disputes, in which multiple individuals or teams have competing claims over who discovered something first. Multiple simultaneous discovery is actually a surprisingly common phenomenon, perhaps largely explained by the idea that previous contributions (including the emergence of contradictions between existing theories, or unexpected empirical results) make a certain concept ready for discovery. Simple priority disputes are often a matter of documenting when certain experiments were performed, or when certain ideas were first articulated to colleagues or recorded in a fixed medium.

Many times the question of exactly which event should qualify as the moment of discovery is difficult to answer. One of the most famous examples of this is the question of the discovery of oxygen. While Carl Wilhelm Scheele and Joseph Priestley were able to concentrate oxygen in the laboratory and characterize its properties, they did not recognize it as a component of air. Priestly actually thought it was *missing* a hypothetical component of air, known as phlogiston, which air was supposed to absorb from materials that are being burned. It was only several years later that Antoine Lavoisier first conceived of the modern notion of oxygen — as a substance that is consumed from the air in the processes of burning and respiration.

By the late 20th century, scientific research has become a large-scale effort, largely accomplished in institutional teams. The amount and frequency of inter-team collaboration has continued to increase, especially after the rise of the Internet, which is a central tool for the modern scientific community. This further complicates the notion of individual accomplishment in science.

Chapter 4

Historiography of Science

The **historiography of science** is the study of the history and methodology of the sub-discipline of history, known as the history of science, including its disciplinary aspects and practices (methods, theories, schools) and to the study of its own historical development ("History of History of Science", i.e., the history of the discipline called History of Science).

Since historiographical debates regarding the proper method for the study of the history of science are sometimes difficult to demarcate from historical controversies regarding the very course of science, it is often (and rightly) the case that the early controversies of the latter kind are considered the inception of the sub-discipline. For example, such discussions permeate the historical writings of the great historian and philosopher of science William Whewell. He is thus often (and rightly) viewed as the grandfather of this discipline; other such distinguished grandfathers are Pierre Duhem and Alexandre Koyré.

As to the explicit presentation of the Historiography of Science it is usually dated in the early Sixties of the 20th century. Thus, for example, in 1965, we find Gerd Buchdahl reporting "A Revolution in Historiography of Science" referring to the innovative studies of Thomas Kuhn and Joseph Agassi. He suggested that these two writers had inaugurated the sub discipline by distinguishing clearly between the history and the historiography of science, as they argued that historiographical views greatly influence the writing of the history of science.

The origins of the discipline

Auguste Comte proposed for the first time that there should be a specific discipline to deal with the history of science. Though scholars and scientists had been chronicling the results of scientific endeavors for centuries (such as William Whewell's *History of the Inductive Sciences* from 1837, and the popular and historical accounts which accompanied the scientific revolution of the 17th century), the development of the distinct academic discipline of the history of science and technology did not occur until the early 20th century, and was intimately bound to the changing role of science during the same time period. The history of science was once exclusively the domain of retired researchers — former scientists whose days in the laboratory had expired but still with a hearty interest in the field — and the rare specialist. However, in the decades since the end of World War II the field has evolved into a full academic discipline, with graduate schools, research institutes, public and private patronage, peer-reviewed journals, and professional societies.

The study of the history of science has had great effects on the philosophy of science, conceptions of the role of science in society, and science policy.

The founding figure of the discipline in the United States was George Sarton, later the founding editor of the journal *Isis*. Sarton and his family fled Belgium after the German invasion in World War I, and after a brief stay in England, he arrived in the United States penniless and unemployed. Sarton began lecturing part-time at several academic institutions, and in

1916 began a two-year appointment at Harvard University. When his appointment did not look like it would be renewed, he appealed to Robert S. Woodward, president of the Carnegie Institution of Washington, for patronage. Woodward gave Sarton a two-year position and in 1920 extended it to a permanent tenured appointment as a Research Associate in the Institution's Department of History.

Though modern scholars do not usually share Sarton's motivations — Sarton saw the history of science as the only genuine example of human progress — the tools he left to the field, the journal *Isis* and the annual volume *Osiris* (both still in print today), provided the foundation of the discipline in the United States.

The Hessen thesis and the birth of externalism

Just as the 1930s were a seminal decade for the development of our modern understanding of science, they were a seminal decade for the history and historiography of science as well. While Sarton taught the first American doctoral students in the discipline, in Europe some of the most influential historians and philosophers of science were first coming into the picture, and the setting of the philosophical battle which is now known as "the Science Wars" was being set.

In 1931, the Second International Congress of the History of Science was convened in London. The papers delivered by the Soviet delegation, led by N.I. Bukharin, quickly invigorated the discipline. Boris Hessen in particular delivered a paper entitled "The Social and Economic Roots of Newton's *Principia*," in which he asserted that Isaac Newton's most famous work was created to cater to the goals and desires of 17th century industry and economy. Hessen asserted that Newton's work was inspired by his economic status and context, that the *Principia* was little more than the solution of technical problems of the bourgeoisie.

Present scholarship has revealed that Hessen's motives were not completely academic. At that time in the Soviet Union, the work of Albert Einstein was under attack by Communist Party philosophers; being supposedly motivated by bourgeois values, it was "bourgeois science" (Graham 1985: 711), and should henceforth be banned. (In many ways this attack was similar to the *Deutsche Physik* movement in Germany which occurred only a few years later.) Hessen's paper was a lobbying tactic: Party philosophers would not challenge the accuracy of Newton's theories, and to show them as being motivated by bourgeois concerns would, in Hessen's eyes, show that scientific validity could exist whatever the motivations were for undertaking it. However, there is little evidence that his paper had any effect in the internal Soviet philosophical battles over Einstein's work.

Despite its lack of effect in his home country, Hessen's thesis had a wide effect in Western history of science. Though Hessen’s work is now easily dismissed as "vulgar Marxism" (Shaffer 1984: 26), its focus on the relationship between society and science was, in its time, seen as novel and inspiring. It was a challenge to the notion that the history of science was the history of individual genius in action, the dominant view at least since William Whewell's *History of the Inductive Sciences* in 1837.

Few contemporary Western readers of Hessen took his paper at face value. His rigid connection between economy and knowledge was not accepted by a majority of historians. However, his assertion that a connection existed between the growth of knowledge and the art of war, and that ballistics played a central part of physics and Newton's world, was viewed with keen interest. In the shadow of the first war to employ chemical weapons, and as the war machines were again gearing up in preparation for another world war, the role between science, technology, and warfare was becoming more interesting to scholars and scientists. Previous views of science as separate from the mundane or vulgar aspects of practical life — the disembodiment of the scientific mind from its context — were becoming less attractive than a view that science and scientists were increasingly embedded in the world in which they worked.

This became reflective in the scholarship of the time as well, with dissertations written on such subjects as "Science and War in the Old Regime," which examined the ways in which military engineering influenced pre-Revolution French scientists.

This method of doing the history of science became known as *externalism*, looking at the manner in which science and scientists are affected, and guided by, their context and the world in which they exist. It is an approach which eschews the notion that the history of science is the development of pure thought over time, one idea leading to another in a contextual bubble which could exist at any place, at any time, if only given the right geniuses.

The contrast to this approach, the method of doing history of science which preceded externalism, became known as *internalism*. Internalist histories of science often focus on the rational reconstruction of scientific ideas and consider the development of these ideas wholly within the scientific world. Although internalist histories of modern science tend to emphasize the norms of modern science, internalist histories can also consider the different systems of thought underlying the development of Babylonian astronomy or Medieval impetus theory

In practice, the line between internalism and externalism can be incredibly fuzzy. Few historians then, or now, would insist that either of these approaches in their extremes paint a wholly complete picture, nor would it necessarily be possible to practice one fully over the other. However, at their heart they contain a basic question about the nature of science: what is the relationship between the producers and consumers of scientific knowledge? The answer to this question must, in some form, inform the method in which the history of science and technology is conducted; conversely, how the history of science and technology is conducted, and what it concludes, can inform the answer to the question. The question itself contains an entire host of philosophical questions: what is the nature of scientific truth? What does objectivity mean in a scientific context? How does change in scientific theories occur?

The historian/sociologist of science Robert K. Merton produced many famous works following Hessen's thesis, which can be seen as reactions to and refinements of Hessen's argument. In his work on science, technology, and society in the 17th century England, Merton sought to introduce an additional category — Puritanism — to explain the growth of science in this period. Merton worked to split Hessen's crude category of economics into smaller subcategories of influence, including transportation, mining, and military technique. Merton also tried to develop empirical, quantitative approaches to showing the influence of external factors on science. Despite these changes, Merton was quick to note his indebtedness to Hessen. Even with his emphasis on external factors, though, Merton differed from Hessen in his interpretation: Merton maintained that while researchers may be inspired and interested by problems which were suggested by extra-scientific factors, ultimately the researcher's interests were driven by "the internal history of the science in question." Merton attempted to delineate externalism and internalism along disciplinary boundaries, with *context* studied by the sociologist of science, and *content* by the historian.

Ludwik Fleck

Around the same period, in 1935, Ludwik Fleck, a Polish medical microbiologist published his Genesis and Development of a Scientific Fact which used a case study in the field of medicine (of the development of the disease concept of Syphilis) to present a thesis about the social nature of knowledge, and in particular science and scientific 'thought styles' (Denkstil) which are the epistemological, conceptual and linguistic styles of scientific (but also non-scientific) 'thought collectives' (Denkkollektiv). This work's importance was not noticed, as [Thaddeus J. Trenn] editor of the English edition published in 1979 writes, 'Fleck's pioneering monograph was published at almost the same time as Karl Popper's Logik der Forschung. But, developed in very different cognitive styles, the books met with contrasting response. In Popper's own words, his book "was surprisingly successful, far beyond Vienna. [...]" [...] It is perhaps most diagnostic that the book received no review notice at all in George Sarton's *Isis*, by then the leading international journal of the history of science.' [pp. xvii-xviii].

As evident from Fleck's book's title, it revolves around the notion that epistemologically, there is nothing stable or realistically true or false about any scientific fact. A fact has a 'genesis' which is grounded in certain theoretic grounds and many times other obscure and fuzzy notions, and it 'develops' as it is subject to dispute and additional research by other scientists. Fleck's work, unlike Hessen's work focuses more on the epistemological and linguistic factors that affect scientific discovery, innovation and progress or development, while Hessen's work focuses on socio-political factors.

Fleck's work was one of the major influences noted by Thomas S. Kuhn which led to the writing his *Structure of Scientific Revolutions*. Kuhn also wrote the foreword to Fleck's English translation.

Vannevar Bush and World War II

The study of the history of science continued to be a small effort until the rise of Big Science after World War II. The influential bureaucrat Vannevar Bush, and the president of Harvard, James Conant, both encouraged the study of the history of science as a way of improving general knowledge about how science worked, and why it was essential to maintain a large scientific workforce.

Thomas Kuhn and the 1960s

From the 1940s through the early 1960s, most histories of science were different forms of a "march of progress", showing science as a triumphant movement towards truth. Many philosophers and historians did of course paint a more nuanced picture, but it was not until the publication of Thomas Kuhn's *The Structure of Scientific Revolutions* that this approach became seriously suspected as being misleading. Kuhn's argument that scientific revolutions worked by paradigm shifts seemed to imply that truth was not the ultimate criterion for science, and the book was extremely influential outside of academia as well. Corresponding with the rise of the environmentalism movement and a general loss of optimism of the power of science and technology unfettered to solve the problems of the world, this new history encouraged many critics to pronounce the preeminence of science to be overthrown.

The discipline today

The discipline today encompasses a wide variety of fields of academic study, ranging from the traditional ones of history, sociology, and philosophy, and a variety of others such as law, architecture, and literature. There is a tendency towards integrating with global history, as well as employing new methodological concepts such as cross-cultural exchange. Historians of science also closely work with scholars from related disciplines such as the history of medicine and Science and technology studies.

Eurocentrism in the historiography of science

Eurocentrism in scientific history are historical accounts written about the development of modern science that attribute all scholarly, technological, and philosophical gains to Europe and marginalize outside contributions. Until Joseph Needham's book series Science and Civilisation in China began in 1954, many historians would write about modern science solely as a European achievement with no significant contributions from civilizations other than the Greeks. Recent historical writings have argued that there was significant influence and contribution from Egyptian, Mesopotamian, Arabic, Indian, and Chinese astronomy and mathematics. The employment of notions of cross-cultural exchange in the study of history of science helps in putting the discipline on the path towards being a non-Eurocentric and non-linear field of study.

Chapter 5

History of Pseudoscience

The **history of pseudoscience** is the study of pseudoscientific theories over time. A pseudoscience is a set of ideas that presents itself as science, while it does not meet the criteria to properly be called such.

Distinguishing between proper science and pseudoscience is sometimes difficult. One popular proposal for demarcation between the two is the falsification criterion, most notably contributed to by the philosopher Karl Popper. In the history of pseudoscience it can be especially hard to separate the two, because some sciences developed from pseudosciences. An example of this is the science chemistry, which traces its origins from the protoscience of alchemy.

The vast diversity in pseudosciences further complicates the history of pseudoscience. Some pseudosciences originated in the pre-scientific era, such as astrology and acupuncture. Others developed as part of an ideology, such as Lysenkoism, or as a response to perceived threats to an ideology. An example of this is creationism, which was developed as a response to the scientific theory of evolution.

Despite failing to meet proper scientific standards, many pseudosciences survive. This is usually due to a persistent core of devotees who refuse to accept scientific criticism of their beliefs, or due to popular misconceptions. Sheer popularity is also a factor, as is attested by astrology which remains popular despite being rejected by a large majority of scientists.

19th century

Among the most notable developments in the history of pseudoscience in the 19th century are the rise of Spiritualism (traced in America to 1848), homeopathy (first formulated in 1796), and phrenology (developed around 1800). Another popular pseudoscientific belief that arose during the 19th century was the idea that there were canals visible on Mars. A relatively mild Christian fundamentalist backlash against the scientific theory of evolution foreshadowed subsequent events in the 20th century.

The study of bumps and fissures in people's skulls to determine their character, **phrenology**, was originally considered a science. It influenced psychiatry and early studies into neuroscience. As science advanced, phrenology was increasingly viewed as a pseudoscience. Halfway through the 19th century, the scientific community had prevailingly abandoned it, although it was not comprehensively tested until much later.

Halfway through the century, **iridology** was invented by the Hungarian physician Ignaz von Peczely. The theory would remain popular throughout the 20th century as well.

Spiritualism (sometimes referred to as "Modern Spiritualism" or "Spiritism") or "Modern American Spiritualism" grew phenomenally during the period. The American version of this movement has been traced to the Fox sisters who in 1848 began claiming the ability to communicate with the dead. The religious movement would remain popular until the 1920s, when renowned magician Harry Houdini began exposing famous mediums and other performers as frauds (see also Harry Houdini#Debunking spiritualists). While the religious beliefs of Spiritualism are not presented as science, and thus are not properly considered pseudoscientific, the movement did spawn numerous pseudoscientific phenomena such as ectoplasm and spirit photography.

The principles of **homeopathy** were first formulated in 1796, by German physician Samuel Hahnemann. At the time, mainstream medicine was a primitive affair and still made use of techniques such as bloodletting. Homeopathic medicine by contrast consisted of extremely diluted substances, which meant that patients basically received water. Compared to the damage often caused by conventional medicine, this was an improvement. During the 1830s homeopathic institutions and schools spread across the US and Europe. Despite these early successes, homeopathy was not without its critics. Its popularity was on the decline before the end of the 19th century, though it has been revived in the 20th century.

The supposed **Martian canals** were first reported in 1877, by the Italian astronomer Giovanni Schiaparelli. The belief in them peaked in the late 19th century, but was widely discredited in the beginning of the 20th century.

The publication of *Atlantis: The Antediluvian World* by politician and author Ignatius L. Donnelly in 1882, renewed interest in the ancient idea of **Atlantis**. This highly advanced society supposedly existed several millennia before the rise of civilizations like Ancient Egypt. It was first mentioned by Plato, as a literary device in two of his dialogues. Other stories of lost continents, such as Mu and Lemuria also arose during the late 19th century.

In 1881 the Dutch Vereniging tegen de Kwakzalverij (English: *Society against Quackery*) was formed to oppose pseudoscientific trends in medicine. It is still active.

20th century

Among the most notable developments to pseudoscience in the 20th century are the rise of Creationism, the demise of Spiritualism, and the first formulation of ancient astronaut theories.

Reflexology, the idea that an undetectable life force connects various parts of the body to the feet and sometimes the hands and ears, was introduced in the US in 1913 as 'zone therapy'.

Creationism arose during the 20th century as a result of various other historical developments. When the modern evolutionary synthesis overcame the eclipse of Darwinism in the first half of the 20th century, American fundamentalist Christians began opposing the teaching of the theory of evolution in public schools. They introduced numerous laws to this effect, one of which was notoriously upheld by the Scopes Trial. In the second half of the century the Space Race caused a renewed interest in science and worry that the USA was falling behind on the Soviet Union. Stricter science standards were adopted and led to the re-introduction of the theory of evolution in the curriculum. The laws against teaching evolution were now ruled unconstitutional, because they violated the separation of church and state. Attempting to evade this ruling, the Christian fundamentalists produced a supposedly secular alternative to evolution, Creationism. Perhaps the most influential publication of this new pseudoscience was *The Genesis Flood* by young earth creationists John C. Whitcomb and Henry M. Morris.

The dawn of the space age also inspired various versions of **ancient astronaut theories**. While differences between the specific theories exists, they share the idea that intelligent extraterrestrials visited Earth in the distant past and made contact with then living humans. Popular authors, such as Erich von Däniken and Zecharia Sitchin, began publishing in the 1960s. Among the most notable publications in the genre is *Chariots of the Gods?*, which appeared in 1968.

The Apollo Moon landings from the 1960s through the 70's gave rise to a number of **Apollo Moon Landing hoax conspiracy theories**. These conspiracy theories are universally ignored by the scientific community, but at the end of the century a Gallup poll showed 6 percent of the American population did not believe the landings were genuine.

Late in the 20th century several prominent skeptical foundations were formed to counter the growth of pseudosciences. In the US, the most notable of these are, in chronological order, the Center for Inquiry (1991), The Skeptics Society (1992), the James Randi Educational Foundation (1996), and the New England Skeptical Society (1996). The

Committee for Skeptical Inquiry, which has similar goals, had already been founded in 1976. It became part of the Center for Inquiry as part of the foundation of the latter in 1991. In the Netherlands Stichting Skepsis was founded in 1987.

21st century

At the beginning of the 21st century, a variety of pseudo scientific theories remain popular and new ones continue to crop up.

The Flat Earth is the idea that is believed to have existed for thousands of years but studies show this is a relative new one starting up in the 1990s when the internet was starting up allowing such ideas to spread much quicker.

Creationism, in the form of **Intelligent Design**, suffered a major legal defeat in the Kitzmiller v. Dover Area School District trial. Judge John E. Jones III ruled that Intelligent Design is inseparable from Creationism, and its teaching in public schools violates the Establishment Clause of the First Amendment. The trial sparked much interest, and was the subject of several documentaries including the award-winning NOVA production *Judgment Day: Intelligent Design on Trial* (2007).

The pseudoscientific idea that **vaccines cause autism** originated in the 1990s, but became prominent in the media during the first decade of the 21st century. Despite a broad scientific consensus against the idea that there is a link between vaccination and autism, several celebrities have joined the debate. Most notable of these is Jenny McCarthy, whose son has autism. In February 2009, surgeon Andrew Wakefield, who published the original research supposedly indicating a link between vaccines and autism, was reported to have fixed the data by The Sunday Times. A hearing by the General Medical Council had already begun in March 2007, examining charges of professional misconduct.

The most notable development in the **ancient astronauts** genre was the opening of Erich von Däniken's Mystery Park in 2003. While the park had a good first year, the number of visitors was much lower than the expected 500,000 a year. This caused financial difficulties, which led to the closure of the park in 2006.

Chapter 6

History of Science in Early Cultures

The **history of science in early cultures** covers protoscience in ancient history, prior to the development of science in the Middle Ages. In prehistoric times, advice and knowledge was passed from generation to generation in an oral tradition. The development of writing enabled knowledge to be stored and communicated across generations with much greater fidelity. Combined with the development of agriculture, which allowed for a surplus of food, it became possible for early civilizations to develop and spend more of their time devoted to tasks other than survival, such as the search for knowledge for knowledge's sake.

Ancient Near East

Mesopotamia

From their beginnings in Sumer (now Iraq) around 3500 BC, the Mesopotamian peoples began to attempt to record some observations of the world with extremely thorough numerical data. A concrete instance of Pythagoras' law was recorded as early as the 18th century BC—the Mesopotamian cuneiform tablet Plimpton 322 records a number of Pythagorean triplets (3,4,5) (5,12,13) ..., dated to approx. 1800 BC, over a millennium before Pythagoras, [1]—but an abstract formulation of the Pythagorean theorem this was not.

Astronomy is a science that lends itself to the recording and study of observations: the rigorous notings of the motions of the stars, planets, and the moon are left on thousands of clay tablets created by scribes. Even today, astronomical periods identified by Mesopotamian scientists are still widely used in Western calendars: the solar year, the lunar month, the seven-day week. Using these data they developed arithmetical methods to compute the changing length of daylight in the course of the year and to predict the appearances and disappearances of the Moon and planets and eclipses of the Sun and Moon. Only a few astronomers' names are known, such as that of Kidinnu, a Chaldean astronomer and mathematician who was contemporary with the Greek astronomers. Kiddinu's value for the solar year is in use for today's calendars. Astronomy and astrology were considered to be the same thing, as evidenced by the practice of this science in Babylonia by priests. Indeed, rather than following the modern trend towards rational science, moving away from superstition and belief, the Mesopotamian astronomy conversely became more astrology-based later in the civilisation - studying the stars in terms of horoscopes and omens, which might explain the popularity of the clay tablets. Hipparchus was to use this data to calculate the precession of the Earth's axis. Fifteen hundred years after Kiddinu, Al-Batani, born in what is now Turkey, would use the collected data and improve Hipparchus' value for the precession of the Earth's axis. Al-Batani's value, 54.5 arc-seconds per year, compares well to the current value of 49.8 arc-seconds per year (26,000 years for Earth's axis to round the circle of nutation).

Babylonian astronomy was "the first and highly successful attempt at giving a refined mathematical description of astronomical phenomena." According to the historian A. Aaboe,

all subsequent varieties of scientific astronomy, in the Hellenistic world, in India, in Islam, and in the West - if not indeed all subsequent endeavour in the exact sciences - depend upon Babylonian astronomy in decisive and fundamental ways.

Egypt

- Further information: Ancient Egyptian medicine, Egyptian astronomy, and Egyptian mathematics

Significant advances in ancient Egypt included astronomy, mathematics and medicine. Their geometry was a necessary outgrowth of surveying to preserve the layout and ownership of farmland, which was flooded annually by the Nile river. The 3-4-5 right triangle and other rules of thumb served to represent rectilinear structures including their post and lintel architecture. Egypt was also a centre of alchemical research for much of the western world.

Egyptian hieroglyphs, a phonetic writing system, have served as the basis for the Egyptian Phoenician alphabet from which the later Hebrew, Greek, Latin, Arabic, and Cyrillic alphabets were derived. The city of Alexandria retained preeminence with its library, which was damaged by fire when it fell under

Roman rule, being completely destroyed before 642. With it a huge amount of antique literature and knowledge was lost.

The Edwin Smith papyrus is one of the first medical documents still extant, and perhaps the earliest document that attempts to describe and analyse the brain: it might be seen as the very beginnings of modern neuroscience. However, while Egyptian medicine had some effective practices, it was not without its ineffective and sometimes harmful practices. Medical historians believe that ancient Egyptian pharmacology, for example, was largely ineffective. Nevertheless, it applies the following components: examination, diagnosis, treatment and prognosis, to the treatment of disease, which display strong parallels to the basic empirical method of science and according to G. E. R. Lloyd played a significant role in the development of this methodology. The Ebers papyrus (c. 1550 BC) also contains evidence of traditional empiricism.

According to a paper published by Michael D. Parkins, 72% of 260 medical prescriptions in the Hearst Papyrus had no curative elements. According to Michael D. Parkins, sewage pharmacology first began in ancient Egypt and was continued through the Middle Ages. Practices such as applying cow dung to wounds, ear piercing and tattooing, and chronic ear infections were important factors in developing tetanus. Frank J. Snoek wrote that Egyptian medicine used fly specks, lizard blood, swine teeth, and other such remedies which he believes could have been harmful.

Persia

In the Sassanid period (226 to 652 AD), great attention was given to mathematics and astronomy. The Academy of Gundishapur is a prominent example in this regard. Astronomical tables—such as the Shahryar Tables—date to this period, and Sassanid observatories were later imitated by Muslim astronomers and astrologers of the Islamic period. In the mid-Sassanid era, an influx of knowledge came to Persia from the West in the form of views and traditions of Greece which, following the spread of Christianity, accompanied Syriac (the official language of Christians as well as the Iranian Nestorians). The Christian schools in Iran have produced great scientists such as Nersi, Farhad, and Marabai. Also, a book was left by Paulus Persa, head of the Iranian Department of Logic and Philosophy of Aristotle, written in Syriac and dictated to Sassanid King Anushiravan.

A fortunate incident for pre-Islamic Iranian science during the Sassanid period was the arrival of eight great scholars from the Hellenistic civilization, who sought refuge in Persia from persecution by the Roman Emperor Justinian. These men were the followers of the Neoplatonic school. King Anushiravan had many discussions with these men and especially with the man named Priscianus. A summary of these discussions was compiled in a book entitled *Solution to the Problems of Khosrow, the King of Persia*, which is now in the Saint Germain Library in Paris. These discussions touched on several subjects, such as philosophy, physiology, metabolisms, and natural science as astronomy. After the establishment of Umayyad and Abbasid states, many Iranian scholars were sent to the capitals of these Islamic dynasties.

In the Early Middle Ages, Persia became a stronghold of Islamic science.

Greco-Roman world

- Scientific thought in Classical Antiquity becomes tangible from the 6th century BC in pre-Socratic philosophy (Thales, Pythagoras). In c. 385 BC, Plato founded the Academy. With Plato's student Aristotle begins the "scientific revolution" of the Hellenistic period culminating in the 3rd to 2nd centuries with scholars such as Eratosthenes, Euclid, Aristarchus of Samos, Hipparchus and Archimedes.

In Classical Antiquity, the inquiry into the workings of the universe took place both in investigations aimed at such practical goals as establishing a reliable calendar or determining how to cure a variety of illnesses and in those abstract investigations known as natural philosophy. The ancient people who are considered the first *scientists* may have thought of themselves as *natural philosophers*, as practitioners of a skilled profession (for example, physicians), or as followers of a religious tradition (for example, temple healers).

The earliest Greek philosophers, known as the pre-Socratics, provided competing answers to the question found in the myths of their neighbours: "How did the ordered cosmos in which we live come to be?" The pre-Socratic philosopher Thales, dubbed the "father of science", was the first to postulate non-supernatural explanations for natural phenomena such as lightning and earthquakes. Pythagoras of

Samos founded the Pythagorean school, which investigated mathematics for its own sake, and was the first to postulate that the Earth is spherical in shape. Subsequently, Plato and Aristotle produced the first systematic discussions of natural philosophy, which did much to shape later investigations of nature. Their development of deductive reasoning was of particular importance and usefulness to later scientific inquiry.

The important legacy of this period included substantial advances in factual knowledge, especially in anatomy, zoology, botany, mineralogy, geography, mathematics and astronomy; an awareness of the importance of certain scientific problems, especially those related to the problem of change and its causes; and a recognition of the methodological importance of applying mathematics to natural phenomena and of undertaking empirical research. In the Hellenistic age scholars frequently employed the principles developed in earlier Greek thought: the application of mathematics and deliberate empirical research, in their scientific investigations. Thus, clear unbroken lines of influence lead from ancient Greek and Hellenistic philosophers, to medieval Muslim philosophers and scientists, to the European Renaissance and Enlightenment, to the secular sciences of the modern day. Neither reason nor inquiry began with the Ancient Greeks, but the Socratic method did, along with the idea of Forms, great advances in geometry, logic, and the natural sciences. Benjamin Farrington, former Professor of Classics at Swansea University wrote:

- "Men were weighing for thousands of years before Archimedes worked out the laws of equilibrium; they must have had practical and intuitional knowledge of the principles involved. What Archimedes did was to sort out the theoretical implications of this practical knowledge and present the resulting body of knowledge as a logically coherent system."

and again:

- "With astonishment we find ourselves on the threshold of modern science. Nor should it be supposed that by some trick of translation the extracts have been given an air of modernity. Far from it. The vocabulary of these writings and their style are the source from which our own vocabulary and style have been derived."
- The level of achievement in Hellenistic astronomy and engineering is impressively shown by the Antikythera mechanism (150-100 BC). The astronomer Aristarchus of Samos was the first known person to propose a heliocentric model of the solar system, while the geographer Eratosthenes accurately calculated the circumference of the Earth. Hipparchus (c. 190 – c. 120 BC) produced the first systematic star catalog. In medicine, Herophilos (335 - 280 BC) was the first to base his conclusions on dissection of the human body and to describe the nervous system. Hippocrates (c. 460 BC – c. 370 BC) and his followers were first to describe many diseases and medical conditions. Galen (129 – c. 200 AD) performed many audacious operations—including brain and eye surgeries— that were not tried again for almost two millennia. The

> mathematician Euclid laid down the foundations of mathematical rigour and introduced the concepts of definition, axiom, theorem and proof still in use today in his *Elements*, considered the most influential textbook ever written. Archimedes, considered one of the greatest mathematicians of all time, is credited with using the method of exhaustion to calculate the area under the arc of a parabola with the summation of an infinite series, and gave a remarkably accurate approximation of pi. He is also known in physics for laying the foundations of hydrostatics and the explanation of the principle of the lever. Theophrastus wrote some of the earliest descriptions of plants and animals, establishing the first taxonomy and looking at minerals in terms of their properties such as hardness. Pliny the Elder produced what is one of the largest encyclopedias of the natural world in 77 AD, and must be regarded as the rightful successor to Theophrastus.

For example, he accurately describes the octahedral shape of the diamond, and proceeds to mention that diamond dust is used by engravers to cut and polish other gems owing to its great hardness. His recognition of the importance of crystal shape is a precursor to modern crystallography, while mention of numerous other minerals presages mineralogy. He also recognises that other minerals have characteristic crystal shapes, but in one example, confuses the crystal habit with the work of lapidaries. He was also the first to recognise that amber was a fossilized resin from pine trees because he had seen samples with trapped insects within them.

India

Excavations at Harappa, Mohenjo-daro and other sites of the Indus Valley Civilization (IVC) have uncovered evidence of the use of "practical mathematics". The people of the IVC manufactured bricks whose dimensions were in the proportion 4:2:1, considered favourable for the stability of a brick structure. They used a standardised system of weights based on the ratios: 1/20, 1/10, 1/5, 1/2, 1, 2, 5, 10, 20, 50, 100, 200, and 500, with the unit weight equaling approximately 28 grammes (and approximately equal to the English ounce or Greek uncia). They mass-produced weights in regular geometrical shapes, which included hexahedra, barrels, cones, and cylinders, thereby demonstrating knowledge of basic geometry.

The inhabitants of Indus civilisation also tried to standardise measurement of length to a high degree of accuracy. They designed a ruler—the *Mohenjo-daro ruler*—whose unit of length (approximately 1.32 inches or 3.4 centimetres) was divided into ten equal parts. Bricks manufactured in ancient Mohenjo-daro often had dimensions that were integral multiples of this unit of length.

Mehrgarh, a Neolithic IVC site, provides the earliest known evidence for *in vivo* drilling of human teeth, with recovered samples dated to 7000-5500 BCE.

Early astronomy in India—like in other cultures— was intertwined with religion. The first textual mention of astronomical concepts comes from the Vedas—religious literature of India. According to Sarma (2008): "One finds in the Rigveda intelligent speculations about the genesis of the universe from nonexistence, the configuration of the universe, the spherical self-supporting earth, and the year of 360 days divided into 12 equal parts of 30 days each with a periodical intercalary month."

Classical Indian astronomy documented in literature spans the Maurya (Vedanga Jyotisha, c. 5th century BCE) to the Vijaynagara(South India) (such as the 16th century Kerala school) periods. The first named authors writing treatises on astronomy emerge from the 5th century, the date when the classical period of Indian astronomy can be said to begin. Besides the theories of Aryabhata in the *Aryabhatiya* and the lost *Arya-siddhānta*, we find the *Pancha-Siddhāntika* of Varahamihira. The astronomy and the astrology of ancient India (Jyotisha) is based upon sidereal calculations, although a tropical system was also used in a few cases.

Alchemy (Rasaśāstra in Sanskrit)was popular in India. It was the Indian alchemist and philosopher Kanada who introduced the concept of 'anu' which he defined as the matter which cannot be subdivided. This is analogous to the concept of atom in modern science.

Linguistics (along with phonology, morphology, etc.) first arose among Indian grammarians studying the Sanskrit language. Aacharya Hemachandrasuri wrote grammars of Sanskrit and Prakrit, poetry, prosody, lexicons, texts on science and logic and many branches of Indian philosophy. The *Siddha-Hema-Śabdanuśāśana* includes six Prakrit languages: the "standard" Prakrit(virtually Maharashtri Prakrit), Shauraseni, Magahi, Paiśācī, the otherwise-unattested Cūlikāpaiśācī and Apabhraṃśa (virtually Gurjar Apabhraṃśa, prevalent in the area of Gujarat and Rajasthan at that time and the precursor of Gujarati language). He gave a detailed grammar of Apabhraṃśa and also illustrated it with the folk literature of the time for better understanding. It is the only known Apabhraṃśa grammar. The Sanskrit grammar of Pāṇini (c. 520 – 460 BCE) contains a particularly detailed description of Sanskrit morphology, phonology and roots, evincing a high level of linguistic insight and analysis.

Ayurveda medicine traces its origins to the Vedas, Atharvaveda in particular, and is connected to Hindu religion. The *Sushruta Samhita* of Sushruta appeared during the 1st millennium BC. Ayurvedic practice was flourishing during the time of Buddha (around 520 BC), and in this period the Ayurvedic practitioners were commonly using Mercuric-sulphur combination based medicines. An important Ayurvedic practitioner of this period was Nagarjuna, accompanied by Surananda, Nagbodhi, Yashodhana, Nityanatha, Govinda, Anantdev, Vagbhatta etc. During the regime of Chandragupta Maurya (375-415 AD), Ayurveda was part of mainstream Indian medical techniques, and continued to be so until the Colonial period.

The main authors of classical Indian mathematics (400 CE to 1200 CE) were scholars like Mahaviracharya, Aryabhata, Brahmagupta, and Bhaskara II. Indian mathematicians made early contributions to the study of the decimal number system, zero, negative numbers, arithmetic, and algebra. In addition, trigonometry, having evolved in the Hellenistic world and having been introduced into ancient India through the translation of Greek works, was further advanced in India, and, in particular, the modern definitions of sine and cosine were developed there. These mathematical concepts were transmitted to the Middle East, China, and Europe and led to further developments that now form the foundations of many areas of mathematics.

China and the Far East

The first recorded observations of solar eclipses and supernovae were made in China. On July 4, 1054, Chinese astronomers observed a *guest star*, a supernova, the remnant of which is now called the Crab Nebula. Korean contributions include similar records of meteor showers and eclipses, particularly from 1500-1750 in the Annals of the Joseon Dynasty. Traditional Chinese Medicine, acupuncture and herbal medicine were also practised, with similar medicine practised in Korea.

Among the earliest inventions were the abacus, the public toilet, and the "shadow clock". Joseph Needham noted the "Four Great Inventions" of China as among some of the most important technological advances; these were the compass, gunpowder, papermaking, and printing, which were later known in Europe by the end of the Middle Ages. The Tang dynasty (AD 618 - 906) in particular was a time of great innovation. A good deal of exchange occurred between Western and Chinese discoveries up to the Qing dynasty.

However, Needham and most scholars recognised that cultural factors prevented these Chinese achievements from developing into what might be considered "modern science".

It was the religious and philosophical framework of the Chinese intellectuals which made them unable to believe in the ideas of laws of nature:

It was not that there was no order in nature for the Chinese, but rather that it was not an order ordained by a rational personal being, and hence there was no conviction that rational personal beings would be able to spell out in their lesser earthly languages the divine code of laws which he had decreed aforetime. The Taoists, indeed, would have scorned such an idea as being too naïve for the subtlety and complexity of the universe as they intuited it.

Chapter 7

Science in Classical Antiquity

Science in classical antiquity encompasses inquiries into the workings of the world or universe aimed at both practical goals (e.g., establishing a reliable calendar or determining how to cure a variety of illnesses) as well as more abstract investigations belonging to natural philosophy. The ancient peoples who are considered today as the first scientists may have thought of themselves as natural philosophers, as practitioners of a skilled profession (for example, physicians), or as followers of a religious tradition (for example, temple healers). Some of these figures include Hippocrates, Aristotle, Euclid, Archimedes, Hipparchus, Galen, and Ptolemy. Their works and commentaries spread throughout the Eastern, Islamic, and Latin worlds and became the wellspring of science.

Classical Greece

Practical knowledge

The practical concerns of the ancient Greeks to establish a calendar is first exemplified by the *Works and Days* of the Greek poet Hesiod, who lived around 700 BC. The *Works and Days* incorporated a calendar, in which the farmer was to regulate seasonal activities by the seasonal appearances and disappearances of the stars, as well as by the phases of the Moon which were held to be propitious or ominous. Around 450

BC we begin to see compilations of the seasonal appearances and disappearances of the stars in texts known as *parapegmata*, which were used to regulate the civil calendars of the Greek city-states on the basis of astronomical observations.

Medicine provides another example of practically oriented investigation of nature among the Ancient Greeks. It has been pointed out that Greek medicine was not the province of a single trained profession and there was no accepted method of qualification of licensing. Physicians in the Hippocratic tradition, temple healers associated with the cult of Asclepius, herb collectors, drug sellers, midwives, and gymnastic trainers all claimed to be qualified as healers in specific contexts and competed actively for patients. This rivalry among these competing traditions contributed to an active public debate about the causes and proper treatment of disease, and about the general methodological approaches of their rivals. In the Hippocratic text, *On the Sacred Disease*, which deals with the nature of epilepsy, the author attacks his rivals (temple healers) for their ignorance and for their love of gain. The author of this text seems modern and progressive when he insists that epilepsy has a natural cause, yet when he comes to explain what that cause is and what the proper treatment would be, his explanation is as short on specific evidence and his treatment as vague as that of his rivals.

There were several acute observers of natural phenomena, especially Aristotle and Theophrastus, who wrote extensively on animals and plants. Theophrastus also produced the first systematic attempt to classify minerals and rocks, summarised in the *Natural History* of Pliny the Elder in 77 AD. The important legacy of this period of Greek science included substantial advances in factual knowledge, especially in anatomy, zoology, botany, mineralogy and astronomy; an awareness of the importance of certain scientific problems, especially those related to the problem of change and its causes; and a recognition of the methodological importance of applying mathematics to natural phenomena and of undertaking empirical research.

Pre-Socratic philosophers

Materialist philosophers

The earliest Greek philosophers, known as the pre-Socratics, were materialists who provided alternative answers to the same question found in the myths of their neighbors: "How did the ordered cosmos in which we live come to be?" But although the question is much the same, their answers and their attitude towards the answers is markedly different. As reported by such later writers as Aristotle, their explanations tended to center on the material source of things.

Thales of Miletus (624–546 BC) considered that all things came to be from and find their sustenance in water. Anaximander (610–546 BC) then suggested that things could not come from a specific substance like water, but rather from something he called the "boundless." Exactly what he meant is uncertain but it has been suggested that it was boundless in its quantity, so that creation would not fail; in its qualities, so that it would not be overpowered by its contrary; in time, as it has no beginning or end; and in space, as it encompasses all things.

Anaximenes (585–525 BC) returned to a concrete material substance, air, which could be altered by rarefaction and condensation. He adduced common observations (the wine stealer) to demonstrate that air was a substance and a simple experiment (breathing on one's hand) to show that it could be altered by rarefaction and condensation.

Heraclitus of Ephesus (about 535–475 BC), then maintained that change, rather than any substance was fundamental, although the element fire seemed to play a central role in this process. Finally, Empedocles of Acragas (490–430 BC), seems to have combined the views of his predecessors, asserting that there are four elements (Earth, Water, Air and Fire) which produce change by mixing and separating under the influence of two opposing "forces" that he called Love and Strife.

All these theories imply that matter is a continuous substance. Two Greek philosophers, Leucippus (first half of the 5th century BC) and Democritus came up with the notion that there were two real entities: atoms, which were small indivisible particles of matter, and the void, which was the empty space in which matter was located. Although all the explanations from Thales to Democritus involve matter, what is more important is the fact that these rival explanations suggest an ongoing process of debate in which alternate theories were put forth and criticized.

Xenophanes of Colophon prefigured paleontology and geology as he thought that periodically the earth and sea mix and turn all to mud, citing several fossils of sea creatures that he had seen.

Pythagorean philosophy

The materialist explanations of the origins of the cosmos were attempts at answering the question of how an organized universe came to be; however, the idea of a random assemblage of elements (e.g., fire or water) producing an ordered universe without the existence of some ordering principle remained problematic to some.

An answer to this conundrum was that of the followers of Pythagoras (c. 582–507 BC), who saw number as the fundamental unchanging entity underlying all the structure of the universe. Although it is difficult to separate fact from legend, it appears that some Pythagoreans believed matter to be made up of ordered arrangements of points according to geometrical principles: triangles, squares, rectangles, or other figures. Likewise, the universe was arranged on the basis of numbers, ratios, and proportions much like musical scales. Philolaus, for instance, held that there were ten heavenly bodies because the sum of 1 + 2 + 3 + 4 gives the perfect number 10. Thus, the Pythagoreans were some of the first to apply mathematical principles to explain the rational basis of an orderly universe— an idea that was to have immense consequences in the development of scientific thought.

Plato and Aristotle

Plato (c. 427–c. 347 BC), perhaps under Pythagorean influence, also identified the ordering principle of the universe as one based on number and geometry. A later account has it that Plato had inscribed at the entrance to the Academy the words

"Let no man ignorant of geometry enter." Although the story is most likely a myth, it nonetheless testifies to Plato's interest in mathematics, which is alluded to in several of his dialogues.

In his philosophy Plato maintained that all material things are imperfect reflections of eternal unchanging ideas, just as all mathematical diagrams are reflections of eternal unchanging mathematical truths. Since Plato believed that material things had an inferior kind of reality, he considered that demonstrative knowledge cannot be achieved by looking at the imperfect material world. Truth is to be found through rational argumentation, analogous to the demonstrations of mathematicians. For instance, Plato recommended that astronomy be studied in terms of abstract geometrical models rather than empirical observations, and proposed that leaders be trained in mathematics in preparation for philosophy.

Aristotle (384–322 BC), who studied at the Academy, nonetheless disagreed with Plato in several important respects. While he agreed that truth must be eternal and unchanging, he maintained that the world is knowable through experience and that we come to know the truth by what we perceive with our senses. For Aristotle, directly observable things are real; ideas (or as he called them, forms) only exist as they express themselves in matter, such as in living things, or in the mind of an observer or artisan.

Aristotle's theory of reality led to a different approach to science:

- First, Aristotle emphasized observation of the material entities which embody the forms.

- Second, he played down (but did not negate) the importance of mathematics.
- Third, he emphasized the process of change where Plato had emphasized eternal unchanging ideas.
- Fourth, he reduced the importance of Plato's ideas to one of four causal factors.

Aristotle thus distinguished between four causes:

- the matter of which a thing was made (the material cause).
- the form into which it was made (the formal cause; similar to Plato's ideas).
- the agent who made the thing (the moving or efficient cause).
- the purpose for which the thing was made (the final cause).

Aristotle insisted that scientific knowledge (Ancient Greek: □πιστήμη, Latin: *scientia*) is knowledge of necessary causes. He and his followers would not accept mere description or prediction as science. In view of this disagreement with Plato, Aristotle established his own school, the Lyceum, which further developed and transmitted his approach to the investigation of nature.

Most characteristic of Aristotle's causes is his final cause, the purpose for which a thing is made. He came to this insight through his biological researches, such as those of marine animals at Lesbos, in which he noted that the organs of animals serve a particular function:

- The absence of chance and the serving of ends are found in the works of nature especially. And the end for the sake of which a thing has been constructed or has come to be belongs to what is beautiful.

Aristotle was one of the most prolific natural philosophers of Antiquity, and developed a comprehensive theory of physics that was a variation of the classical theory of the elements (earth, water, fire, air, and aether). In his theory, the light elements (fire and air) have a natural tendency to move away from the center of the universe while the heavy elements (earth and water) have a natural tendency to move toward the center of the universe, thereby forming a spherical earth. Since the celestial bodies (i.e., the planets and stars) were seen to move in circles, he concluded that they must be made of a fifth element, which he called aether.

Aristotle used intuitive ideas to justify his reasoning and could point to the falling stone, rising flames, or pouring water to illustrate his theory. His laws of motion emphasized the common observation that friction was an omnipresent phenomenon: that any body in motion would, unless acted upon, *come to rest*. He also proposed that heavier objects fall faster, and that voids were impossible.

Theophrastus and the Peripatetics

Aristotle's successor at the Lyceum was Theophrastus, who wrote valuable books describing plant and animal life. His works are regarded as the first to put botany and zoology on a systematic footing.

One of Theophrastus' achievements is his work on mineralogy, with descriptions of ores and minerals known to the world at that time. He made some shrewd observations of their properties. For example, he made the first known reference to the phenomenon, now known to be caused by pyroelectricity, that the mineral tourmaline attracts straws and bits of wood when heated. Pliny the Elder makes clear references to his use of the work in his *Natural History* of 77 AD, while updating and making much new information available on minerals himself. From both these early texts was to emerge the science of mineralogy, and ultimately geology. Both authors describe the sources of the minerals they discuss in the various mines exploited in their time, so their works should be regarded not just as early scientific texts, but also important for the history of engineering and the history of technology.

Other notable peripatetics include Strato, who was a tutor in the court of the Ptolemies and who devoted time to physical research, Eudemus, who edited Aristotle's works and wrote the first books on the history of science, and Demetrius of Phalerum, who governed Athens for a time and later helped establish the Library of Alexandria.

Hellenistic period

The military campaigns of Alexander the Great spread Greek thought to Egypt, Asia Minor, Persia, up to the Indus River. The resulting Hellenistic civilization produced many seats of learning, such as those in Alexandria, Antioch, and Pergamum, along with the migration of many Greek speaking populations across several territories. Hellenistic science differed from

Greek science in at least two respects: first, it benefited from the cross-fertilization of Greek ideas with those that had developed in other non-Hellenic civilizations; secondly, to some extent, it was supported by royal patrons in the kingdoms founded by Alexander's successors. The city of Alexandria, in particular, became a major center of scientific research in the 3rd century BC. Two institutions established there during the reigns of Ptolemy I Soter (reigned 323–283 BC) and Ptolemy II Philadelphus (reigned 281–246 BC) were the Library and the Museum. Unlike Plato's Academy and Aristotle's Lyceum, these institutions were officially supported by the Ptolemies; although the extent of patronage could be precarious, depending on the policies of the current ruler.

Hellenistic scholars frequently employed the principles developed in earlier Greek thought, including the application of mathematics and deliberate empirical research, in their scientific investigations.

The interpretation of Hellenistic science varies widely. At one extreme is the view of English classical scholar Cornford, who believed that "all the most important and original work was done in the three centuries from 600 to 300 BC". At the other end is the view of Italian physicist and mathematician Lucio Russo, who claims that the scientific method was actually born in the 3rd century BCE, only to be largely forgotten during the Roman period and not revived again until the Renaissance.

Technology

The level of Hellenistic achievement in astronomy and engineering is impressively shown by the Antikythera mechanism (150–100 BCE). It is a 37-gear mechanical computer which computed the motions of the Sun and Moon, including lunar and solar eclipses predicted on the basis of astronomical periods believed to have been learned from the Babylonians. Devices of this sort that use differential gearing are not known to have been engineered again until the 10th century, when a simpler eight-geared luni-solar calculator incorporated into an astrolabe was described by Persian scholar Al-Biruni. Similarly complex devices were also developed by other Muslim engineers and astronomers during the Middle Ages.

Medicine

In medicine, Herophilos (335–280 BCE) was the first to base his conclusions on dissection of the human body and to describe the nervous system. For this, he is often called as "the father of anatomy"

Mathematics

Beginning with the Hellenistic period, Greek mathematics and astronomy reached a level of sophistication not matched for several centuries afterward. Much of the work represented by scholars active in this period was of a very advanced level. There is also evidence of combining mathematical knowledge with high levels of technical expertise, as found for instance in the construction of massive building projects (e.g., the Syracusia), or in Eratosthenes' (276 – 195 BCE) measurement of the distance between the Sun and the Earth and the size of the Earth.

Although few in number, Hellenistic mathematicians actively communicated with each other; publication consisted of passing and copying someone's work among colleagues. Among their accomplishments is the work of Euclid (325 – 265 BCE), which includes the *Elements*, a canon of geometry and elementary number theory for many centuries. Archimedes (287 – 212 BCE) found many remarkable results, such as the sum of an infinite geometric series in *Quadrature of the Parabola*, an approximation to the value π in *Measurement of the Circle*, and a nomenclature to express very large numbers in the *Sand Reckoner*.

The most characteristic product of Greek mathematics may be the theory of conic sections, which was largely developed in the Hellenistic period, primarily by Apollonius (262 – 190 BCE). The methods used made no explicit use of algebra, nor trigonometry, the latter appearing around the time of Hipparchus (190 – 120 BCE).

Astronomy

Aristarchus of Samos (310 – 230 BCE) was an ancient Greek astronomer and mathematician who presented the first known heliocentric model that placed the Sun at the center of the known universe, with the Earth revolving around the Sun once a year and rotating about its axis once a day. Aristarchus also estimated the sizes of the Sun and Moon as compared to Earth's size, and the distances to the Sun and Moon. His heliocentric model did not find many adherents in antiquity but did influence some early modern astronomers, such as Nicolaus Copernicus, who was aware of the heliocentric theory of Aristarchus.

In the 2nd century BC, Hipparchus discovered precession, calculated the size and distance of the Moon and invented the earliest known astronomical devices such as the astrolabe. Hipparchus also created a comprehensive catalog of 1020 stars, and most of the constellations of the northern hemisphere derive from Greek astronomy. It has recently been claimed that a celestial globe based on Hipparchus's star catalog sits atop the broad shoulders of a large 2nd-century Roman statue known as the Farnese Atlas.

Roman era

Science during the Roman Empire period was concerned with systematizing knowledge gained in the preceding Hellenistic period and the knowledge from the vast areas the Romans had conquered. It was largely their work that would be passed on to later civilizations.

Even though science continued under Roman rule, Latin texts were mainly compilations drawing on earlier Greek work. Advanced scientific research and teaching continued to be carried on in Greek. Such Greek and Hellenistic works as survived were preserved and developed later in the Byzantine Empire and then in the Islamic world. Late Roman attempts to translate Greek writings into Latin had limited success (e.g., Boethius), and direct knowledge of most ancient Greek texts only reached western Europe from the 12th century onwards.

Pliny

Of particular importance is the *Naturalis Historia* of Pliny the Elder published in 77 CE, one of the most extensive compilations of the natural world which survived the Dark Ages. Pliny does not simply list materials and objects but also seeks explanations of phenomena. Thus he is the first to correctly describe the origin of amber as being the fossilized resin of pine trees. He makes the inference from the observation of trapped insects within some amber samples. The *Naturalis Historia* divides neatly into the organic world of plants and animals, and the realm of inorganic matter, although there are frequent digressions in each section. He is especially interested in not just describing the occurrence of plants, animals and insects, but also their exploitation (or abuse) by man. The description of metals and minerals is particularly detailed, and valuable as being the most extensive compilation still available from the ancient world. Although much of the work was compiled by judicious use of written sources, Pliny gives an eyewitness account of gold mining in Spain, where he was stationed as an officer. Pliny is especially significant because he provides full bibliographic details of the earlier authors and their works he uses and consults. Because his encyclopaedia survived the Dark Ages, we know of these lost works, even if the texts themselves have disappeared. The book was one of the first to be printed in 1489, and became a standard reference work for Renaissance scholars, as well as an inspiration for the development of a scientific and rational approach to the world.

Ptolemy

Claudius Ptolemy (c. 100-170 CE), living in or around Alexandria, carried out a massive program centering on the writing of about a dozen books on astronomy, astrology, optics, harmonics, and cartography. Despite their severe style and high technicality, a great deal of them have survived, in some cases the sole remnants of their kind of scientific writing from antiquity. Though ranging widely in subject matter, two major themes run through Ptolemy's works: mathematical modelling of physical phenomena, and methods of visual representation of physical reality.

Characteristically of Ptolemy's research program is his combination of theoretical analysis with empirical considerations. A prime example of this approach is his systematized study of astronomy. Ptolemy's *Mathēmatikē Syntaxis* (Ancient Greek: ΜαθηματικὴΣύνταξις), better known as the *Almagest*, sought to improve on the work of his predecessors by building astronomy not only upon a secure mathematical basis but also by demonstrating the relationship between astronomical observations and the resulting astronomical theory. In his *Planetary Hypotheses*, Ptolemy describes in detail physical representations of his mathematical models found in the *Almagest*, presumably for didactic purposes. Likewise, the *Geography* was concerned with the drawing of accurate maps using astronomical information, at least in principle. Apart from astronomy, both the *Harmonics* and the *Optics* contain (in addition to mathematical analyses of sound and sight, respectively) instructions on how to construct and use experimental instruments to corroborate theory.

Ptolemy's thoroughness and his preoccupation with ease of presentation (for instance, in his widespread use of tables) virtually guaranteed that earlier work on these subjects be neglected or considered obsolete, to the extent that almost nothing remains of the works Ptolemy often refers. His astronomical work in particular defined the method and subject matter of future research for centuries, and the Ptolemaic system became the dominant model for the motions of the heavens until the seventeenth century.

Galen

Around the same time, the Roman-era physician Galen (c. 129-210 CE) codified and somewhat built upon Hellenistic knowledge of anatomy and physiology. His careful dissections and observations of dogs, pigs, and Barbary apes, his descriptions (based on these and the works of earlier authors) of such structures as the nervous system, heart, and kidneys, and his demonstrations that, for instance, arteries carry blood instead of air became a central part of medical knowledge for well over a thousand years.

Hero

Hero of Alexandria was a Greco-Egyptian mathematician and engineer who is often considered to be the greatest experimenter of antiquity. Among his most famous inventions was a windwheel, constituting the earliest instance of wind harnessing on land, and a well-recognized description of a steam-powered device called an aeolipile, which was the first-recorded steam engine.

Chapter 8

Byzantine Science

Byzantine science played an important role in the transmission of classical knowledge to the Islamic world and to Renaissance Italy, and also in the transmission of Islamic science to Renaissance Italy. Its rich historiographical tradition preserved ancient knowledge upon which splendid art, architecture, literature and technological achievements were built.

Byzantines stood behind several technological advancements.

Classical and ecclesiastical studies

Byzantine science was essentially classical science. Therefore, Byzantine science was in every period closely connected with ancient-pagan philosophy, and metaphysics. Despite some opposition to pagan learning, many of the most distinguished classical scholars held high office in the Church. The writings of antiquity never ceased to be cultivated in the Byzantine Empire due to the impetus given to classical studies by the Academy of Athens in the 4th and 5th centuries, the vigor of the philosophical academy of Alexandria, and to the services of the University of Constantinople, which concerned itself entirely with secular subjects, to the exclusion of theology, which was taught in the Patriarchical Academy. Even the latter offered instruction in the ancient classics, and included literary, philosophical, and scientific texts in its curriculum. The monastic schools concentrated upon the Bible, theology, and liturgy. Therefore, the monastic scriptoria expended most of their efforts upon the transcription of ecclesiastical manuscripts, while ancient-pagan literature was transcribed, summarized, excerpted, and annotated by laymen or clergy like Photios, Arethas of Caesarea, Eustathius of Thessalonica, and Basilius Bessarion.

Mathematics

Byzantine scientists preserved and continued the legacy of the great Ancient Greek mathematicians and put mathematics in practice. In early Byzantium (5th to 7th century) the architects and mathematicians Isidore of Miletus and Anthemius of Tralles used complex mathematical formulas to construct the great Hagia Sophia church, a technological breakthrough for its time and for centuries afterwards due to its striking geometry, bold design and height. In middle Byzantium (8th to 12th century) mathematicians like Michael Psellos considered mathematics as a way to interpret the world.

Physics

John Philoponus, also known as John the Grammarian, was an Alexandrian philologist, Aristotelian commentator and Christian theologian, and author of philosophical treatises and theological works. He was the first who criticized Aristotle and attacked Aristotle's theory of the free fall. His criticism of

Aristotelian physics was an inspiration for Galileo Galilei many centuries later; Galileo cited Philoponus substantially in his works, and followed him in refuting Aristotelian physics.

The theory of impetus was also invented in the Byzantine Empire.

Ship mill is an invention made by the Byzantines, and was constructed in order to mill grains by using the energy of the stream of water. The technology eventually spread to the rest of Europe and was in use until ca. 1800.

Medicine

Medicine was one of the sciences in which the Byzantines improved on their Greco-Roman predecessors, starting from Galen. As a result, Byzantine medicine had an influence on Islamic medicine as well as the medicine of the Renaissance.

The concept of hospital as institution to offer medical care and possibility of a cure for the patients due to the ideals of Christian charity, rather than just merely a place to die, appeared in Byzantine Empire.

The first known example of separating conjoined twins happened in the Byzantine Empire in the 10th century when a pair of conjoined twins from Armenia came eventually to Constantinople. Many years later one of them died, so the surgeons in Constantinople decided to remove the body of the dead one. The result was partly successful as the surviving twin lived in three days before dying. But the fact that the second person survived for few days after separating it, was so impressive that it was mentioned a century and half years later again by historians. The next case of separating conjoined twins will be recorded first about 700 years later in the year 1689 in Germany.

Incendiary weapons

Greek fire was an incendiary weapon used by the Byzantine Empire. The Byzantines typically used it in naval battles to great effect as it could continue burning even on water. It provided a technological advantage, and was responsible for many key Byzantine military victories, most notably the salvation of Constantinople from two Arab sieges, thus securing the Empire's survival. Greek fire proper however was invented in c. 672, and is ascribed by the chronicler Theophanes to Kallinikos, an architect from Heliopolis in the former province of Phoenice, by then overrun by the Muslim conquests. It has been argued that no single person invented the Greek fire, but that it was rather “invented by the chemists in Constantinople who had inherited the discoveries of the Alexandrian chemical school...”.

The grenade first appeared in the Byzantine Empire, where rudimentary incendiary grenades made of ceramic jars holding glass or nails were made and used on battlefields.

Byzantine and Islamic science

During the Middle Ages, there was frequently an exchange of works between Byzantine and Islamic science. The Byzantine

Empire initially provided the medieval Islamic world with Ancient and early Medieval Greek texts on astronomy, mathematics and philosophy for translation into Arabic as the Byzantine Empire was the leading center of scientific scholarship in the region at the beginning of the Middle Ages. Later as the Caliphate and other medieval Islamic cultures became the leading centers of scientific knowledge, Byzantine scientists such as Gregory Chioniades, who had visited the famous Maragheh observatory, translated books on Islamic astronomy, mathematics and science into Medieval Greek, including for example the works of Ja'far ibn Muhammad Abu Ma'shar al-Balkhi, Ibn Yunus, Al-Khazini (who was of Byzantine Greek descent but raised in a Persian culture), Muhammad ibn Mūsā al-Khwārizmī and Nasīr al-Dīn al-Tūsī (such as the *Zij-i Ilkhani* and other Zij treatises) among others.

There were also some Byzantine scientists who used Arabic transliterations to describe certain scientific concepts instead of the equivalent Ancient Greek terms (such as the use of the Arabic *talei* instead of the Ancient Greek *horoscopus*). Byzantine science thus played an important role in not only transmitting ancient Greek knowledge to Western Europe and the Islamic world, but in also transmitting Arabic knowledge to Western Europe. Some historians suspect that Copernicus or another European author had access to an Arabic astronomical text, resulting in the transmission of the Tusi-couple, an astronomical model developed by Nasir al-Din al-Tusi that later appeared in the work of Nicolaus Copernicus. Byzantine scientists also became acquainted with Sassanid and Indian astronomy through citations in some Arabic works.

Humanism and Renaissance

During the 12th century the Byzantines produced their model of early Renaissance humanism as a renaissance of interest in classical authors, however, during the centuries before, (9-12) Renaissance Humanism and wanting for classical learning was prominent during the Macedonian Renaissance, and continued into what we see now as the 12th century Renaissance under the Komnenoi. In Eustathius of Thessalonica Byzantine humanism found its most characteristic expression. During the 13th and 14th centuries, a period of intense creative activity, Byzantine humanism approached its zenith, and manifested a striking analogy to the contemporaneous Italian humanism. Byzantine humanism believed in the vitality of classical civilization, and of its sciences, and its proponents occupied themselves with scientific sciences.

Despite the political, and military decline of these last two centuries, the Empire saw a flourishing of science and literature, often described as the "Palaeologean" or "Last Byzantine Renaissance". Some of this era's most eminent representatives are: Maximus Planudes, Manuel Moschopulus, Demetrius Triclinius and Thomas Magister. The Academy at Trebizond, highly influenced by Persian sciences, became a renowned center for the study of astronomy, and other mathematical sciences, and medicine attracted the interest of almost all scholars. In the final century of the Empire Byzantine grammarians were those principally responsible for carrying in person, and in writing ancient Greek grammatical, and literary studies to early Renaissance Italy, and among them Manuel Chrysoloras was involved over the never achieved union of the Churches.

Chapter 9

Science in the Medieval Islamic World

Science in the medieval Islamic world was the science developed and practised during the Islamic Golden Age under the Umayyads of Córdoba, the Abbadids of Seville, the Samanids, the Ziyarids, the Buyids in Persia, the Abbasid Caliphate and beyond, spanning the period roughly between 786 and 1258. Islamic scientific achievements encompassed a wide range of subject areas, especially astronomy, mathematics, and medicine. Other subjects of scientific inquiry included alchemy and chemistry, botany and agronomy, geography and cartography, ophthalmology, pharmacology, physics, and zoology.

Medieval Islamic science had practical purposes as well as the goal of understanding. For example, astronomy was useful for determining the *Qibla*, the direction in which to pray, botany had practical application in agriculture, as in the works of Ibn Bassal and Ibn al-'Awwam, and geography enabled Abu Zayd al-Balkhi to make accurate maps. Islamic mathematicians such as Al-Khwarizmi, Avicenna and Jamshīd al-Kāshī made advances in algebra, trigonometry, geometry and Arabic numerals. Islamic doctors described diseases like smallpox and measles, and challenged classical Greek medical theory. Al-Biruni, Avicenna and others described the preparation of hundreds of drugs made from medicinal plants and chemical compounds. Islamic physicists such as Ibn Al-Haytham, Al-

Bīrūnī and others studied optics and mechanics as well as astronomy, and criticised Aristotle's view of motion.

The significance of medieval Islamic science has been debated by historians. The traditionalist view holds that it lacked innovation, and was mainly important for handing on ancient knowledge to medieval Europe. The revisionist view holds that it constituted a scientific revolution. Whatever the case, science flourished across a wide area around the Mediterranean and further afield, for several centuries, in a wide range of institutions.

Context

The Islamic era began in 622. Islamic armies conquered Arabia, Egypt and Mesopotamia, eventually displacing the Persian and Byzantine Empires from the region. Within a century, Islam had reached the area of present-day Portugal in the west and Central Asia in the east. The Islamic Golden Age (roughly between 786 and 1258) spanned the period of the Abbasid Caliphate (750–1258), with stable political structures and flourishing trade. Major religious and cultural works of the Islamic empire were translated into Arabic and occasionally Persian. Islamic culture inherited Greek, Indic, Assyrian and Persian influences. A new common civilisation formed, based on Islam. An era of high culture and innovation ensued, with rapid growth in population and cities. The Arab Agricultural Revolution in the countryside brought more crops and improved agricultural technology, especially irrigation. This supported the larger population and enabled culture to flourish. From the 9th century onwards, scholars such as Al-

Kindi translated Indian, Assyrian, Sasanian (Persian) and Greek knowledge, including the works of Aristotle, into Arabic. These translations supported advances by scientists across the Islamic world.

Islamic science survived the initial Christian reconquest of Spain, including the fall of Seville in 1248, as work continued in the eastern centres (such as in Persia). After the completion of the Spanish reconquest in 1492, the Islamic world went into an economic and cultural decline. The Abbasid caliphate was followed by the Ottoman Empire (c. 1299–1922), centred in Turkey, and the Safavid Empire (1501–1736), centred in Persia, where work in the arts and sciences continued.

Fields of inquiry

Medieval Islamic scientific achievements encompassed a wide range of subject areas, especially mathematics, astronomy, and medicine. Other subjects of scientific inquiry included physics, alchemy and chemistry, ophthalmology, and geography and cartography.

Alchemy and chemistry

The early Islamic period saw the establishment of theoretical frameworks in alchemy and chemistry. The sulfur-mercury theory of metals, first found in pseudo-Apollonius of Tyana's *Sirr al-khalīqa* ("The Secret of Creation", c. 750–850) and in the writings attributed to Jabir ibn Hayyan (written c. 850–950), remained the basis of theories of metallic composition until the 18th century. The *Emerald Tablet*, a cryptic text that all later alchemists up to and including Isaac Newton saw as the foundation of their art, first occurs in the *Sirr al-khalīqa* and in one of the works attributed to Jabir. In practical chemistry, the works of Jabir, and those of the Persian alchemist and physician Abu Bakr al-Razi (854–925), contain the earliest systematic classifications of chemical substances. Alchemists were also interested in artificially creating such substances. Jabir describes the synthesis of ammonium chloride (sal ammoniac) from organic substances, and Abu Bakr al-Razi experimented with the heating of ammonium chloride, vitriol, and other salts, which would eventually lead to the discovery of the mineral acids by 13th-century Latin alchemists such as pseudo-Geber.

Astronomy and cosmology

Astronomy became a major discipline within Islamic science. Astronomers devoted effort both towards understanding the nature of the cosmos and to practical purposes. One application involved determining the *Qibla*, the direction to face during prayer. Another was astrology, predicting events affecting human life and selecting suitable times for actions such as going to war or founding a city. Al-Battani (850–922) accurately determined the length of the solar year. He contributed to the Tables of Toledo, used by astronomers to predict the movements of the sun, moon and planets across the sky. Copernicus (1473-1543) later used some of Al-Battani's astronomic tables.

Al-Zarqali (1028–1087) developed a more accurate astrolabe, used for centuries afterwards. He constructed a water clock in Toledo, discovered that the Sun's apogee moves slowly relative to the fixed stars, and obtained a good estimate of its motion for its rate of change. Nasir al-Din al-Tusi (1201–1274) wrote an important revision to Ptolemy's 2nd-century celestial model. When Tusi became Helagu's astrologer, he was given an observatory and gained access to Chinese techniques and observations. He developed trigonometry as a separate field, and compiled the most accurate astronomical tables available up to that time.

Botany and agronomy

The study of the natural world extended to a detailed examination of plants. The work done proved directly useful in the unprecedented growth of pharmacology across the Islamic world. Al-Dinawari (815–896) popularised botany in the Islamic world with his six-volume *Kitab al-Nabat* (*Book of Plants*). Only volumes 3 and 5 have survived, with part of volume 6 reconstructed from quoted passages. The surviving text describes 637 plants in alphabetical order from the letters *sin* to *ya*, so the whole book must have covered several thousand kinds of plants. Al-Dinawari described the phases of plant growth and the production of flowers and fruit. The thirteenth century encyclopedia compiled by Zakariya al-Qazwini (1203–1283) – *ʿAjā'ib al-makhlūqāt* (The Wonders of Creation) – contained, among many other topics, both realistic botany and fantastic accounts. For example, he described trees which grew birds on their twigs in place of leaves, but which could only be found in the far-distant British Isles. The use and cultivation of plants was documented in the 11th century by Muhammad bin Ibrāhīm Ibn Bassāl of Toledo in his book *Dīwān al-filāha* (The Court of Agriculture), and by Ibn al-'Awwam al-Ishbīlī (also called Abū l-Khayr al-Ishbīlī) of Seville in his 12th century book *Kitāb al-Filāha* (Treatise on Agriculture). Ibn Bassāl had travelled widely across the Islamic world, returning with a detailed knowledge of agronomy that fed into the Arab Agricultural Revolution. His practical and systematic book describes over 180 plants and how to propagate and care for them. It covered leaf- and root-vegetables, herbs, spices and trees.

Geography and cartography

- The spread of Islam across Western Asia and North Africa encouraged an unprecedented growth in trade and travel by land and sea as far away as Southeast Asia, China, much of Africa, Scandinavia and even Iceland. Geographers worked to compile increasingly accurate maps of the known world, starting from many existing but fragmentary sources. Abu Zayd al-Balkhi (850–934), founder of the Balkhīschool of cartography in Baghdad, wrote an atlas called *Figures of the Regions* (Suwar al-aqalim). Al-Biruni (973–1048) measured the radius of the earth using a new method. It involved observing the height of a mountain at Nandana (now in Pakistan). Al-Idrisi (1100–1166) drew a map of the world for Roger, the Norman King of Sicily (ruled 1105-1154). He also wrote the *Tabula Rogeriana* (Book of Roger), a geographic study of the peoples, climates, resources and industries of the whole of the world known at that time. The Ottoman admiral Piri Reis (c. 1470–1553) made a map of the New World and West Africa in 1513. He made use of maps from Greece, Portugal, Muslim sources, and perhaps one made by Christopher Columbus. He represented a part of a major tradition of Ottoman cartography.

Mathematics

- Islamic mathematicians gathered, organised and clarified the mathematics they inherited from ancient Egypt, Greece, India, Mesopotamia and Persia, and went on to make innovations of their own. Islamic mathematics covered algebra, geometry and arithmetic. Algebra was mainly used for recreation: it had few practical applications at that time. Geometry was studied at different levels. Some texts contain practical geometrical rules for surveying and for measuring figures. Theoretical geometry was a necessary prerequisite for understanding astronomy and optics, and it required years of concentrated work. Early in the Abbasid caliphate (founded 750), soon after the foundation of Baghdad in 762, some mathematical knowledge was assimilated by al-Mansur's group of scientists from the pre-Islamic Persian tradition in astronomy. Astronomers from India were invited to the court of the caliph in the late eighth century; they explained the rudimentary trigonometrical techniques used in Indian astronomy. Ancient Greek works such as Ptolemy's *Almagest* and Euclid's *Elements* were translated into Arabic. By the second half of the ninth century, Islamic mathematicians were already making contributions to the most sophisticated parts of

Greek geometry. Islamic mathematics reached its apogee in the Eastern part of the Islamic world between the tenth and twelfth centuries. Most medieval Islamic mathematicians wrote in Arabic, others in Persian.

Al-Khwarizmi (8th–9th centuries) was instrumental in the adoption of the Hindu-Arabic numeral system and the development of algebra, introduced methods of simplifying equations, and used Euclidean geometry in his proofs. He was the first to treat algebra as an independent discipline in its own right, and presented the first systematic solution of linear and quadratic equations. Ibn Ishaq al-Kindi (801–873) worked on cryptography for the Abbasid Caliphate, and gave the first known recorded explanation of cryptanalysis and the first description of the method of frequency analysis. Avicenna (c. 980–1037) contributed to mathematical techniques such as casting out nines. Thābit ibn Qurra (835–901) calculated the solution to a chessboard problem involving an exponential series. Al-Farabi (c. 870–950) attempted to describe, geometrically, the repeating patterns popular in Islamic decorative motifs in his book *Spiritual Crafts and Natural Secrets in the Details of Geometrical Figures*. Omar Khayyam (1048–1131), known in the West as a poet, calculated the length of the year to within 5 decimal places, and found geometric solutions to all 13 forms of cubic equations, developing some quadratic equations still in use. Jamshīd al-Kāshī (c. 1380–1429) is credited with several theorems of trigonometry, including the law of cosines, also known as Al-Kashi's Theorem. He has been credited with the invention of decimal fractions, and with a method like Horner's to calculate roots. He calculated π correctly to 17 significant figures.

Sometime around the seventh century, Islamic scholars adopted the Hindu-Arabic numeral system, describing their use in a standard type of text *fī l-ḥisāb al hindī*, (On the numbers of the Indians). A distinctive Western Arabic variant of the Eastern Arabic numerals began to emerge around the 10th century in the Maghreb and Al-Andalus (sometimes called *ghubar* numerals, though the term is not always accepted), which are the direct ancestor of the modern Arabic numerals used throughout the world.

Medicine

Islamic society paid careful attention to medicine, following a *hadith* enjoining the preservation of good health. Its physicians inherited knowledge and traditional medical beliefs from the civilisations of classical Greece, Rome, Syria, Persia and India. These included the writings of Hippocrates such as on the theory of the four humours, and the theories of Galen. al-Razi (c. 854–925/935) identified smallpox and measles, and recognized fever as a part of the body's defenses. He wrote a 23-volume compendium of Chinese, Indian, Persian, Syriac and Greek medicine. al-Razi questioned the classical Greek medical theory of how the four humours regulate life processes. He challenged Galen's work on several fronts, including the treatment of bloodletting, arguing that it was effective. al-Zahrawi (936–1013) was a surgeon whose most important surviving work is referred to as *al-Tasrif* (Medical Knowledge). It is a 30-volume set mainly discussing medical symptoms, treatments, and pharmacology. The last volume, on surgery, describes surgical instruments, supplies, and pioneering procedures. Avicenna (c. 980–1037) wrote the major medical textbook, *The Canon of Medicine*. Ibn al-Nafis (1213–1288) wrote an influential book on medicine; it largely replaced Avicenna's *Canon* in the Islamic world. He wrote commentaries on Galen and on Avicenna's works. One of these commentaries, discovered in 1924, described the circulation of blood through the lungs.

Optics and ophthalmology

Optics developed rapidly in this period. By the ninth century, there were works on physiological, geometrical and physical optics. Topics covered included mirror reflection. Hunayn ibn Ishaq (809–873) wrote the book *Ten Treatises on the Eye*; this remained influential in the West until the 17th century. Abbas ibn Firnas (810–887) developed lenses for magnification and the improvement of vision. Ibn Sahl (c. 940–1000) discovered the law of refraction known as Snell's law. He used the law to produce the first Aspheric lenses that focused light without geometric aberrations.

In the eleventh century Ibn al-Haytham (Alhazen, 965–1040) rejected the Greek ideas about vision, whether the Aristotelian tradition that held that the form of the perceived object entered the eye (but not its matter), or that of Euclid and Ptolemy which held that the eye emitted a ray. Al-Haytham proposed in his *Book of Optics* that vision occurs by way of light rays forming a cone with its vertex at the center of the eye. He suggested that light was reflected from different surfaces in different directions, thus causing objects to look different. He argued further that the mathematics of reflection and refraction needed to be consistent with the anatomy of the eye. He was also an early proponent of the scientific method, the concept that a hypothesis must be proved by experiments based on confirmable procedures or mathematical evidence, five centuries before Renaissance scientists.

Pharmacology

Advances in botany and chemistry in the Islamic world encouraged developments in pharmacology. Muhammad ibn Zakarīya Rāzi (Rhazes) (865–915) promoted the medical uses of chemical compounds. Abu al-Qasim al-Zahrawi (Abulcasis) (936–1013) pioneered the preparation of medicines by sublimation and distillation. His *Liber servitoris* provides instructions for preparing "simples" from which were compounded the complex drugs then used. Sabur Ibn Sahl (died 869) was the first physician to describe a large variety of drugs and remedies for ailments. Al-Muwaffaq, in the 10th century, wrote *The foundations of the true properties of Remedies*, describing chemicals such as arsenious oxide and silicic acid. He distinguished between sodium carbonate and potassium carbonate, and drew attention to the poisonous nature of copper compounds, especially copper vitriol, and also of lead compounds. Al-Biruni (973–1050) wrote the *Kitab al-Saydalah* (*The Book of Drugs*), describing in detail the properties of drugs, the role of pharmacy and the duties of the pharmacist. Ibn Sina (Avicenna) described 700 preparations, their properties, their mode of action and their indications. He devoted a whole volume to simples in *The Canon of Medicine*. Works by Masawaih al-Mardini (c. 925–1015) and by Ibn al-Wafid (1008–1074) were printed in Latin more than fifty times, appearing as *De Medicinis universalibus et particularibus* by Mesue the Younger (died 1015) and as the *Medicamentis* *simplicibus* by Abenguefit (c. 997 – 1074) respectively. Peter of Abano (1250–1316) translated and added a supplement to the work of al-Mardini under the title *De Veneris*. Ibn al-Baytar (1197–1248), in his *Al-Jami fi al-Tibb*, described a thousand simples and drugs based directly on Mediterranean plants collected along the entire coast between Syria and Spain, for the first time exceeding the coverage provided by Dioscorides in classical times. Islamic physicians such as Ibn Sina described clinical trials for determining the efficacy of medical drugs and substances.

Physics

The fields of physics studied in this period, apart from optics and astronomy which are described separately, are aspects of mechanics: statics, dynamics, kinematics and motion. In the sixth century John Philoponus (c. 490 – c. 570) rejected the Aristotelian view of motion. He argued instead that an object acquires an inclination to move when it has a motive power impressed on it. In the eleventh century Ibn Sina adopted roughly the same idea, namely that a moving object has force which is dissipated by external agents like air resistance. Ibn Sina distinguished between "force" and "inclination" (*mayl*); he claimed that an object gained *mayl* when the object is in opposition to its natural motion. He concluded that continuation of motion depends on the inclination that is transferred to the object, and that the object remains in motion until the *mayl* is spent. He also claimed that a projectile in a vacuum would not stop unless it is acted upon. That view accords with Newton's first law of motion, on inertia. As a non-Aristotelian suggestion, it was essentially abandoned until it was described as "impetus" by Jean Buridan (c. 1295–1363), who was influenced by Ibn Sina's *Book of Healing*.

In the *Shadows*, Abū Ray�ān al-Bīrūnī (973–1048) describes non-uniform motion as the result of acceleration. Ibn-Sina's theory of *mayl* tried to relate the velocity and weight of a moving object, a precursor of the concept of momentum. Aristotle's theory of motion stated that a constant force produces a uniform motion; Abu'l-Barakāt al-Baghdādī (c. 1080 – 1164/5) disagreed, arguing that velocity and acceleration are two different things, and that force is proportional to acceleration, not to velocity.

Ibn Bajjah (Avempace, c. 1085–1138) proposed that for every force there is a reaction force. While he did not specify that these forces be equal, this was still an early version of Newton's third law of motion.

The Banu Musa brothers, Jafar-Muhammad, Ahmad and al-Hasan (c. early 9th century) invented automated devices described in their Book of Ingenious Devices. Advances on the subject were also made by al-Jazari and Ibn Ma'ruf.

Zoology

Many classical works, including those of Aristotle, were transmitted from Greek to Syriac, then to Arabic, then to Latin in the Middle Ages. Aristotle's zoology remained dominant in its field for two thousand years. The *Kitāb al-Hayawān* (كتابـــــــــــالحيوان, English: *Book of Animals*) is a 9th-century Arabic translation of *History of Animals*: 1–10, *On the Parts of Animals*: 11–14, and *Generation of Animals*: 15–19.

The book was mentioned by Al-Kindī (died 850), and commented on by Avicenna (Ibn Sīnā) in his *The Book of Healing*. Avempace (Ibn Bājja) and Averroes (Ibn Rushd) commented on and criticised *On the Parts of Animals* and *Generation of Animals*.

Significance

Historians of science differ in their views of the significance of the scientific accomplishments in the medieval Islamic world. The traditionalist view, exemplified by Bertrand Russell, holds that Islamic science, while admirable in many technical ways, lacked the intellectual energy required for innovation and was chiefly important for preserving ancient knowledge, and handing it on to medieval Europe. The revisionist view, exemplified by Abdus Salam, George Saliba and John M. Hobson hold that a Muslim scientific revolution occurred during the Middle Ages. Scholars such as Donald Routledge Hill and Ahmad Y. Hassan argue that Islam was the driving force behind these scientific achievements.

According to Ahmed Dallal, science in medieval Islam was "practiced on a scale unprecedented in earlier human history or even contemporary human history". Toby Huff takes the view that, although science in the Islamic world did produce localized innovations, it did not lead to a scientific revolution, which in his view required an ethos that existed in Europe in the twelfth and thirteenth centuries, but not elsewhere in the world. Will Durant, Fielding H. Garrison, Hossein Nasr and Bernard Lewis held that Muslim scientists helped in laying the foundations for an experimental science with their contributions to the scientific method and their empirical, experimental and quantitative approach to scientific inquiry.

James E. McClellan III and Harold Dorn, reviewing the place of Islamic science in world history, comment that the positive achievement of Islamic science was simply to flourish, for centuries, in a wide range of institutions from observatories to libraries, madrasas to hospitals and courts, both at the height of the Islamic golden age and for some centuries afterwards. It plainly did not lead to a scientific revolution like that in Early modern Europe, but in their view, any such external comparison is just an attempt to impose "chronologically and culturally alien standards" on a successful medieval culture.

Chapter 10

Timeline of Science and Engineering in the Muslim World

This **timeline of science and engineering** in the **Muslim world** covers the time period from the eighth century AD to the introduction of European science to the Muslim world in the nineteenth century. All year dates are given according to the Gregorian calendar except where noted.

Eighth Century

Astronomers and astrologers

- **d 777 CE** Ibrāhīm al-Fazārī**Ibrahim ibn Habib ibn Sulayman ibn Samura ibn Jundab al-Fazari** (Arabic: إبراهيمبنحبيببنسليمانبنسمرةبنجندبالفزاري) (died 777 CE) was an 8th-century Muslim mathematician and astronomer at the Abbasid court of the Caliph Al-Mansur (r. 754–775). He should not to be confused with his son Muḥammad ibn Ibrāhīm al-Fazārī, also an astronomer. He composed various astronomical writings ("on the astrolabe", "on the armillary spheres", "on the calendar").

- **d 796Muhammad ibn Ibrahim ibn Habib ibn Sulayman ibn Samra ibn Jundab al-Fazari** (Arabic: إبراهيمبنحبيببنسليمانبنسمرةبنجندبالفزاري) (died 796 or 806) was a Muslim philosopher, mathematician and astronomer. He is not to be confused with his father Ibrāhīm al-Fazārī, also an astronomer and mathematician. Some sources refer to him as an Arab, other sources state that he was a Persian. Al-Fazārī translated many scientific books into Arabic and Persian. He is credited to have built the first astrolabe in the Islamic world. Along with Yaʿqūb ibn Ṭāriq and his father he helped translate the Indian astronomical text by Brahmagupta (fl. 7th century), the *Brāhmasphuṭasiddhānta*, into Arabic as *Az-Zīj ʿalā Sinī al-ʿArab.*, or the *Sindhind.* This translation was possibly the vehicle by means of which the Hindu numerals were transmitted from India to Islam.

Biologists, neuroscientists, and psychologists

- **(654–728)** Ibn Sirin **Muhammad Ibn Sirin** (Arabic: محمدبنسيرين) (born in Basra) was a Muslim mystic and interpreter of dreams who lived in the 8th century. He was a contemporary of Anas ibn Malik. Once regarded as the same person as Achmet son of Seirim, this is no longer believed to be true, as shown by Maria Mavroudi.

Mathematics

- **780 – 850:al-Khwarizmi** Developed the "calculus of resolution and juxtaposition" (*hisab al-jabr w'al-*

muqabala), more briefly referred to as al-jabr, or algebra.

Ninth Century

Chemistry

- **801 – 873:** Al-Kindi writes on the distillation of wine as that of rose water and gives 107 recipes for perfumes, in his book Kitab Kimia al-'otoor wa al-tas`eedat (book of the chemistry of perfumes and distillations.)
- **854 – 930:** Al-Razi wrote on Naft (naphta or petroleum) and its distillates in his book "Kitab sirr al-asrar" (book of the secret of secrets.) When choosing a site to build Baghdad's hospital, he hung pieces of fresh meat in different parts of the city. The location where the meat took the longest to rot was the one he chose for building the hospital. Advocated that patients not be told their real condition so that fear or despair do not affect the healing process. Wrote on alkali, caustic soda, soap and glycerine. Gave descriptions of equipment processes and methods in his book Kitab al-Asrar (book of secrets) in 925.

Mathematics

- **826 – 901:** Thabit ibn Qurra (Latinized, Thebit.) Studied at Baghdad's House of Wisdom under the Banu Musa brothers. Discovered a theorem that enables pairs of amicable numbers to be found. Later, al-Baghdadi (b. 980) developed a variant of the theorem.

Miscellaneous

- ***c.* 810:** Bayt al-Hikma (House of Wisdom) set up in Baghdad. There Greek and Indian mathematical and astronomy works are translated into Arabic.
- **810 – 887:** Abbas ibn Firnas. Planetarium, artificial crystals. According to one account that was written seven centuries after his death, Ibn Firnas was injured during an elevated winged trial flight.

Tenth Century

By this century, three systems of counting are used in the Arab world. Finger-reckoning arithmetic, with numerals written entirely in words, used by the business community; the sexagesimal system, a remnant originating with the Babylonians, with numerals denoted by letters of the arabic alphabet and used by Arab mathematicians in astronomical work; and the Indian numeral system, which was used with various sets of symbols. Its arithmetic at first required the use of a dust board (a sort of handheld blackboard) because "the methods required moving the numbers around in the calculation and rubbing some out as the calculation proceeded."

Chemistry

- **957:** Abul Hasan Ali Al-Masudi, wrote on the reaction of alkali water with zaj (vitriol) water giving sulfuric acid.

Mathematics

- **920:** al-Uqlidisi. Modified arithmetic methods for the Indian numeral system to make it possible for pen and paper use. Hitherto, doing calculations with the Indian numerals necessitated the use of a dust board as noted earlier.
- **940:** Born Abu'l-Wafa al-Buzjani. Wrote several treatises using the finger-counting system of arithmetic and was also an expert on the Indian numerals system. About the Indian system, he wrote: "[It] did not find application in business circles and among the population of the Eastern Caliphate for a long time." Using the Indian numeral system, abu'l Wafa was able to extract roots.
- **980:** al-Baghdadi Studied a slight variant of Thabit ibn Qurra's theorem on amicable numbers. Al-Baghdadi also wrote about and compared the three systems of counting and arithmetic used in the region during this period.

Eleventh Century

Mathematics

- **1048 – 1131:** Omar Khayyam. Persian mathematician and poet. "Gave a complete classification of cubic equations with geometric solutions found by means of intersecting conic sections.". Extracted roots using the decimal system (the Indian numeral system).

Twelfth Century

Cartography

- **1100–1165:** Muhammad al-Idrisi, aka Idris al-Saqalli aka al-sharif al-idrissi of Andalusia and Sicily. Known for having drawn some of the most advanced ancient world maps.

Mathematics

- **1130–1180:** Al-Samawal. An important member of al-Karaji's school of algebra. Gave this definition of algebra: "[it is concerned] with operating on unknowns using all the arithmetical tools, in the same way as the arithmetician operates on the known."

- **1135:** Sharaf al-Dīn al-Ṭūsī. Follows al-Khayyam's application of algebra of geometry, rather than follow the general development that came through al-Karaji's school of algebra. Wrote a treatise on cubic equations which describes thus: "[the treatise] represents an essential contribution to another algebra which aimed to study curves by means of equations, thus inaugurating the beginning of algebraic geometry." (quoted in).

Thirteenth Century

Chemistry

- Al-Jawbari describes the preparation of rose water in the work "Book of Selected Disclosure of Secrets" (Kitab kashf al-Asrar).
- Materials; glassmaking: Arabic manuscript on the manufacture of false gemstones and diamonds. Also describes spirits of alum, spirits of saltpetre and spirits of salts (hydrochloric acid).
- An Arabic manuscript written in Syriac script gives description of various chemical materials and their properties such as sulfuric acid, sal-ammoniac, saltpetre and zaj (vitriol).

Mathematics

- **1260:** al-Farisi. Gave a new proof of Thabit ibn Qurra's theorem, introducing important new ideas concerning factorization and combinatorial methods. He also gave the pair of amicable numbers 17296, 18416 which have also been joint attributed to Fermat as well as Thabit ibn Qurra.

Miscellaneous

- Mechanical engineering: Ismail al-Jazari described 100 mechanical devices, some 80 of which are trick vessels of various kinds, along with instructions on how to construct them
- Medicine; Scientific method: Ibn Al-Nafis (1213–1288) Damascene physician and anatomist. Discovered the lesser circulatory system (the cycle involving the ventricles of the heart and the lungs) and described the mechanism of breathing and its relation to the blood and how it nourishes on air in the lungs. Followed a "constructivist" path of the smaller circulatory system: "blood is purified in the lungs for the continuance of life and providing the body with the ability to work". During his time, the common view was that blood originates in the liver then travels to the right ventricle, then on to the organs of the body; another contemporary view was that blood is filtered through the diaphragm where it mixes with the air coming from the lungs. Ibn al-Nafis discredited all these views including ones by Galen and Avicenna (ibn Sina). At least an

illustration of his manuscript is still extant. William Harvey explained the circulatory system without reference to ibn al-Nafis in 1628. Ibn al-Nafis extolled the study of comparative anatomy in his "Explaining the dissection of [Avicenna's] Al-Qanoon" which includes a preface, and citations of sources. Emphasized the rigours of verification by measurement, observation and experiment. Subjected conventional wisdom of his time to a critical review and verified it with experiment and observation, discarding errors.

Fourteenth Century

Astronomy

- **1393–1449:** Ulugh Beg commissions an observatory at Samarqand in present-day Uzbekistan.

Mathematics

- **1380–1429:** al-Kashi. According to, "contributed to the development of decimal fractions not only for approximating algebraic numbers, but also for real numbers such as pi. His contribution to decimal fractions is so major that for many years he was considered as their inventor. Although not the first to do so, al-Kashi gave an algorithm for calculating nth roots which is a special case of the methods given many centuries later by Ruffini and Horner."

Fifteenth Century

Mathematics

- Ibn al-Banna and al-Qalasadi used symbols for mathematics "and, although we do not know exactly when their use began, we know that symbols were used at least a century before this."

Miscellaneous

- Astronomy and mathematics: Ibn Masoud (Ghayyathuddin Jamshid ibn Mohamed ibn mas`oud, d. 1424 or 1436.) Wrote on the decimal system. Computed and observed the solar eclipses of 809AH, 810AH and 811AH, after being invited by Ulugh Beg, based in Samarqand to pursue his study of mathematics, astronomy and physics. His works include "The Key of arithmetics"; "Discoveries in mathematics"; "The Decimal point"; "the benefits of the zero". The contents of the Benefits of the Zero are an introduction followed by five essays: On whole number arithmetic; On fractional arithmetic; on astrology; on areas; on finding the unknowns [unknown variables]. He also wrote a "Thesis on the sine and the chord"; "thesis on the circumference" in which he found the ratio of the circumference to the radius of a circle to sixteen decimal places; "The garden of gardens" or "promenade of the gardens" describing an instrument he devised and used at the Samarqand observatory to compile an ephemeris, and for computing solar and lunar eclipses; The ephemeris "Zayj Al-Khaqani" which also includes mathematical tables and corrections of the ephemeris by Al-Tusi; "Thesis on finding the first-degree sine".

Seventeenth century

Mathematics

- The Arabic mathematician Mohammed Baqir Yazdi discovered the pair of amicable numbers 9,363,584 and 9,437,056 for which he is jointly credited with Descartes.

Eighteenth century

- A 17th century celestial globe was made by Diya' ad-din Muhammad in Lahore, 1663 (now in Pakistan). It is now housed at the National Museum of Scotland. It is encircled by a meridian ring and a horizon ring. The latitude angle of 32° indicates that the globe was made in the Lahore workshop. This specific 'workshop claims 21 signed globes—the largest number from a single shop' making this globe a good example of Celestial Globe production at its peak.

Chapter 11

European Science in the Middle Ages

European science in the Middle Ages comprised the study of nature, mathematics and natural philosophy in medieval Europe. Following the fall of the Western Roman Empire and the decline in knowledge of Greek, Christian Western Europe was cut off from an important source of ancient learning. Although a range of Christian clerics and scholars from Isidore and Bede to Jean Buridan and Nicole Oresme maintained the spirit of rational inquiry, Western Europe would see a period of scientific decline during the Early Middle Ages. However, by the time of the High Middle Ages, the region had rallied and was on its way to once more taking the lead in scientific discovery. Scholarship and scientific discoveries of the Late Middle Ages laid the groundwork for the Scientific Revolution of the Early Modern Period.

According to Pierre Duhem, who founded the academic study of medieval science as a critique of the Enlightenment-positivist theory of a 17th-century anti-Aristotelian and anticlerical scientific revolution, the various conceptual origins of that alleged revolution lay in the 12th to 14th centuries, in the works of churchmen such as Thomas Aquinas and Buridan.

In the context of this article, "Western Europe" refers to the European cultures bound together by the Catholic Church and the Latin language.

Western Europe

As Roman imperial power effectively ended in the West during the 5th century, Western Europe entered the Middle Ages with great difficulties that affected the continent's intellectual production dramatically. Most classical scientific treatises of classical antiquity written in Greek were unavailable, leaving only simplified summaries and compilations. Nonetheless, Roman and early medieval scientific texts were read and studied, contributing to the understanding of nature as a coherent system functioning under divinely established laws that could be comprehended in the light of reason. This study continued through the Early Middle Ages, and with the Renaissance of the 12th century, interest in this study was revitalized through the translation of Greek and Arabic scientific texts. Scientific study further developed within the emerging medieval universities, where these texts were studied and elaborated, leading to new insights into the phenomena of the universe. These advances are virtually unknown to the lay public of today, partly because most theories advanced in medieval science are today obsolete, and partly because of the caricature of Middle Ages as a supposedly "Dark Age" which placed "the word of religious authorities over personal experience and rational activity."

Early Middle Ages (AD 476–1000)

In the ancient world, Greek had been the primary language of science. Even under the Roman Empire, Latin texts drew extensively on Greek work, some pre-Roman, some contemporary; while advanced scientific research and teaching continued to be carried on in the Hellenistic side of the empire, in Greek. Late Roman attempts to translate Greek writings into Latin had limited success.

As the knowledge of Greek declined during the transition to the Middle Ages, the Latin West found itself cut off from its Greek philosophical and scientific roots. Most scientific inquiry came to be based on information gleaned from sources which were often incomplete and posed serious problems of interpretation. Latin-speakers who wanted to learn about science only had access to books by such Roman writers as Calcidius, Macrobius, Martianus Capella, Boethius, Cassiodorus, and later Latin encyclopedists. Much had to be gleaned from non-scientific sources: Roman surveying manuals were read for what geometry was included.

De-urbanization reduced the scope of education and by the 6th century teaching and learning moved to monastic and cathedral schools, with the center of education being the study of the Bible. Education of the laity survived modestly in Italy, Spain, and the southern part of Gaul, where Roman influences were most long-lasting. In the 7th century, learning began to emerge in Ireland and the Celtic lands, where Latin was a foreign language and Latin texts were eagerly studied and taught.

The leading scholars of the early centuries were clergymen for whom the study of nature was but a small part of their interest. They lived in an atmosphere which provided little institutional support for the disinterested study of natural phenomena. The study of nature was pursued more for practical reasons than as an abstract inquiry: the need to care for the sick led to the study of medicine and of ancient texts on drugs, the need for monks to determine the proper time to pray led them to study the motion of the stars, the need to compute the date of Easter led them to study and teach rudimentary mathematics and the motions of the Sun and Moon. Modern readers may find it disconcerting that sometimes the same works discuss both the technical details of natural phenomena and their symbolic significance.

Around 800, Charles the Great, assisted by the English monk Alcuin of York, undertook what has become known as the Carolingian Renaissance, a program of cultural revitalization and educational reform. The chief scientific aspect of Charlemagne's educational reform concerned the study and teaching of astronomy, both as a practical art that clerics required to compute the date of Easter and as a theoretical discipline. From the year 787 on, decrees were issued recommending the restoration of old schools and the founding of new ones throughout the empire. Institutionally, these new schools were either under the responsibility of a monastery, a cathedral or a noble court.

The scientific work of the period after Charlemagne was not so much concerned with original investigation as it was with the active study and investigation of ancient Roman scientific texts. This investigation paved the way for the later effort of Western scholars to recover and translate ancient Greek texts in philosophy and the sciences.

High Middle Ages (AD 1000–1300)

Beginning around the year 1050, European scholars built upon their existing knowledge by seeking out ancient learning in Greek and Arabic texts which they translated into Latin. They encountered a wide range of classical Greek texts, some of which had earlier been translated into Arabic, accompanied by commentaries and independent works by Islamic thinkers.

Gerard of Cremona is a good example: an Italian who traveled to Spain to copy a single text, he stayed on to translate some seventy works. His biography describes how he came to Toledo: "He was trained from childhood at centers of philosophical study and had come to a knowledge of all that was known to the Latins; but for love of the *Almagest*, which he could not find at all among the Latins, he went to Toledo; there, seeing the abundance of books in Arabic on every subject and regretting the poverty of the Latins in these things, he learned the Arabic language, in order to be able to translate."

This period also saw the birth of medieval universities, which benefited materially from the translated texts and provided a new infrastructure for scientific communities. Some of these new universities were registered as an institution of international excellence by the Holy Roman Empire, receiving the title of *Studium Generale*. Most of the early *Studia Generali* were found in Italy, France, England, and Spain, and these were considered the most prestigious places of learning in Europe. This list quickly grew as new universities were founded throughout Europe. As early as the 13th century, scholars from a *Studium Generale* were encouraged to give lecture courses at other institutes across Europe and to share documents, and this led to the current academic culture seen in modern European universities.

The rediscovery of the works of Aristotle allowed the full development of the new Christian philosophy and the method of scholasticism. By 1200 there were reasonably accurate Latin translations of the main works of Aristotle, Euclid, Ptolemy, Archimedes, and Galen—that is, of all the intellectually crucial ancient authors except Plato. Also, many of the medieval Arabic and Jewish key texts, such as the main works of Avicenna, Averroes and Maimonides now became available in Latin. During the 13th century, scholastics expanded the natural philosophy of these texts by commentaries (associated with teaching in the universities) and independent treatises. Notable among these were the works of Robert Grosseteste, Roger Bacon, John of Sacrobosco, Albertus Magnus, and Duns Scotus.

Scholastics believed in empiricism and supporting Roman Catholic doctrines through secular study, reason, and logic. The most famous was Thomas Aquinas (later declared a "Doctor of the Church"), who led the move away from the Platonic and Augustinian and towards Aristotelianism (although natural philosophy was not his main concern). Meanwhile, precursors of the modern scientific method can be seen already in Grosseteste's emphasis on mathematics as a way to understand nature and in the empirical approach admired by Roger Bacon.

Grosseteste was the founder of the famous Oxford Franciscan school. He built his work on Aristotle's vision of the dual path of scientific reasoning. Concluding from particular observations into a universal law, and then back again: from universal laws to prediction of particulars. Grosseteste called this "resolution and composition". Further, Grosseteste said that both paths should be verified through experimentation in order to verify the principals. These ideas established a tradition that carried forward to Padua and Galileo Galilei in the 17th century.

Under the tuition of Grosseteste and inspired by the writings of Arab alchemists who had preserved and built upon Aristotle's portrait of induction, Bacon described a repeating cycle of *observation*, *hypothesis*, *experimentation*, and the need for independent *verification*. He recorded the manner in which he conducted his experiments in precise detail so that others could reproduce and independently test his results - a cornerstone of the scientific method, and a continuation of the work of researchers like Al Battani.

Bacon and Grosseteste conducted investigations into optics, although much of it was similar to what was being done at the time by Arab scholars. Bacon did make a major contribution to the development of science in medieval Europe by writing to the Pope to encourage the study of natural science in university courses and compiling several volumes recording the state of scientific knowledge in many fields at the time. He described the possible construction of a telescope, but there is no strong evidence of his having made one.

Late Middle Ages (AD 1300–1500)

The first half of the 14th century saw the scientific work of great thinkers. The logic studies by William of Occam led him to postulate a specific formulation of the principle of parsimony, known today as Occam's razor. This principle is one of the main heuristics used by modern science to select between two or more underdetermined theories, though it is only fair to point out that this principle was employed explicitly by both Aquinas and Aristotle before him.

As Western scholars became more aware (and more accepting) of controversial scientific treatises of the Byzantine and Islamic Empires these readings sparked new insights and speculation. The works of the early Byzantine scholar John Philoponus inspired Western scholars such as Jean Buridan to question the received wisdom of Aristotle's mechanics. Buridan developed the theory of impetus which was a step towards the modern concept of inertia. Buridan anticipated Isaac Newton when he wrote:

. . . after leaving the arm of the thrower, the projectile would be moved by an impetus given to it by the thrower and would continue to be moved as long as the impetus remained stronger than the resistance, and would be of infinite duration were it not diminished and corrupted by a contrary force resisting it or by something inclining it to a contrary motion.

Thomas Bradwardine and his partners, the Oxford Calculators of Merton College, Oxford, distinguished kinematics from dynamics, emphasizing kinematics, and investigating instantaneous velocity. They formulated the mean speed theorem: *a body moving with constant velocity travels distance and time equal to an accelerated body whose velocity is half the final speed of the accelerated body*. They also demonstrated this theorem—the essence of "The Law of Falling Bodies"—long before Galileo, who has gotten the credit for this.

In his turn, Nicole Oresme showed that the reasons proposed by the physics of Aristotle against the movement of the Earth were not valid and adduced the argument of simplicity for the theory that the Earth moves, and *not* the heavens. Despite this argument in favor of the Earth's motion, Oresme fell back on the commonly held opinion that "everyone maintains, and I think myself, that the heavens do move and not the earth."

The historian of science Ronald Numbers notes that the modern scientific assumption of methodological naturalism can be also traced back to the work of these medieval thinkers:

By the late Middle Ages the search for natural causes had come to typify the work of Christian natural philosophers. Although characteristically leaving the door open for the possibility of direct divine intervention, they frequently expressed contempt for soft-minded contemporaries who invoked miracles rather than searching for natural explanations. The University of Paris cleric Jean Buridan (a. 1295–ca. 1358), described as "perhaps the most brilliant arts master of the Middle Ages," contrasted the philosopher's search for "appropriate natural causes" with the common folk's erroneous habit of attributing unusual astronomical phenomena to the supernatural. In the fourteenth century the natural philosopher Nicole Oresme (ca. 1320–82), who went on to become a Roman Catholic bishop, admonished that, in discussing various marvels of nature, "there is no reason to take recourse to the heavens, the last refuge of the weak, or demons, or to our glorious God as if He would produce these effects directly, more so than those effects whose causes we believe are well known to us."

However, a series of events that would be known as the Crisis of the Late Middle Ages was under its way. When came the Black Death of 1348, it sealed a sudden end to the previous period of scientific progress. The plague killed a third of the people in Europe, especially in the crowded conditions of the towns, where the heart of innovations lay. Recurrences of the plague and other disasters caused a continuing decline of population for a century.

Renaissance (15th century)

The 15th century saw the beginning of the cultural movement of the Renaissance. The rediscovery of Greek scientific texts, both ancient and medieval, was accelerated as the Byzantine Empire fell to the Ottoman Turks and many Byzantine scholars sought refuge in the West, particularly Italy.

Also, the invention of printing was to have great effect on European society: the facilitated dissemination of the printed word democratized learning and allowed a faster propagation of new ideas.

When the Renaissance moved to Northern Europe that science would be revived, by figures as Copernicus, Francis Bacon, and Descartes (though Descartes is often described as an early Enlightenment thinker, rather than a late Renaissance one).

Byzantine and Islamic influences

Byzantine interactions

Byzantine science played an important role in the transmission of classical knowledge to the Islamic world and to Renaissance Italy, and also in the transmission of medieval Arabic knowledge to Renaissance Italy. Its rich historiographical tradition preserved ancient knowledge upon which splendid art, architecture, literature and technological achievements were built.

Byzantine scientists preserved and continued the legacy of the great Ancient Greek mathematicians and put mathematics in practice. In early Byzantium (5th to 7th century) the architects and mathematicians Isidore of Miletus and Anthemius of Tralles used complex mathematical formulas to construct the great "Hagia Sophia" temple, a magnificent technological breakthrough for its time and for centuries afterwards due to its striking geometry, bold design and height. In late Byzantium (9th to 12th century) mathematicians like Michael Psellos considered mathematics as a way to interpret the world.

John Philoponus, a Byzantine scholar in the 500s, was the first person to systematically question Aristotle's teaching of physics. This served as an inspiration for Galileo Galilei ten centuries later as Galileo cited Philoponus substantially in his works when Galileo also argued why Aristotelian physics was flawed during the Scientific Revolution.

Islamic interactions

The Byzantine Empire initially provided the medieval Islamic world with Ancient Greek texts on astronomy and mathematics for translation into Arabic. Later with the emerging of the Muslim world, Byzantine scientists such as Gregory Chioniades translated Arabic texts on Islamic astronomy, mathematics and science into Medieval Greek, including the works of Ja'far ibn Muhammad Abu Ma'shar al-Balkhi, Ibn Yunus, al-Khazini, Muhammad ibn Mūsā al-Khwārizmī and Nasīr al-Dīn al-Tūsī among others. There were also some Byzantine scientists who used Arabic transliterations to describe certain scientific concepts instead of the equivalent Ancient Greek terms (such as the use of the Arabic *talei* instead of the Ancient Greek *horoscopus*). Byzantine science thus played an important role in not only transmitting ancient Greek knowledge to Western Europe and the Islamic world, but in also transmitting Islamic knowledge to Western Europe. Byzantine scientists also became acquainted with Sassanid and Indian astronomy through citations in some Arabic works.