HISTORY OF SCIENCE

Volume 2

Benjamin Kent

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Chapter 12

Science in the Renaissance

During the Renaissance, great advances occurred in geography, astronomy, chemistry, physics, mathematics, manufacturing, anatomy and engineering. The collection of ancient scientific texts began in earnest at the start of the 15th century and continued up to the Fall of Constantinople in 1453, and the invention of printing democratized learning and allowed a faster propagation of new ideas. Nevertheless, some have seen the Renaissance, at least in its initial period, as one of scientific backwardness. Historians like George Sarton and Lynn Thorndike criticized how the Renaissance affected science, arguing that progress was slowed for some amount of time. Humanists favored human-centered subjects like politics and history over study of natural philosophy or applied mathematics. More recently, however, scholars have acknowledged the positive influence of the Renaissance on mathematics and science, pointing to factors like the rediscovery of lost or obscure texts and the increased emphasis on the study of language and the correct reading of texts.

Marie Boas Hall coined the term **Scientific Renaissance** to designate the early phase of the Scientific Revolution, 1450–1630. More recently, Peter Dear has argued for a two-phase model of early modern science: a *Scientific Renaissance* of the 15th and 16th centuries, focused on the restoration of the natural knowledge of the ancients; and a *Scientific Revolution* of the 17th century, when scientists shifted from recovery to innovation.

Context

During and after the Renaissance of the 12th century, Europe experienced an intellectual revitalization, especially with regard to the investigation of the natural world. In the 14th century, however, a series of events that would come to be known as the Crisis of the Late Middle Ages was underway. When the Black Death came, it wiped out so many lives it affected the entire system. It brought a sudden end to the previous period of massive scientific change. The plague killed 25–50% 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.

The Renaissance

The 14th century saw the beginning of the cultural movement of the Renaissance. By the early 15th century, an international search for ancient manuscripts was underway and would continue unabated until the Fall of Constantinople in 1453, when many Byzantine scholars had to seek refuge in the West, particularly Italy. Likewise, the invention of the printing press 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.

Initially, there were no new developments in physics or astronomy, and the reverence for classical sources further enshrined the Aristotelian and Ptolemaic views of the universe.

Renaissance philosophy lost much of its rigor as the rules of logic and deduction were seen as secondary to intuition and emotion. At the same time, Renaissance humanism stressed that nature came to be viewed as an animate spiritual creation that was not governed by laws or mathematics. Only later, when no more manuscripts could be found, did humanists turn from collecting to editing and translating them, and new scientific work began with the work of such figures as Copernicus, Cardano, and Vesalius.

Important developments

Alchemy

Alchemy is the study of the transmutation of materials through obscure processes. It is sometimes described as an early form of chemistry. One of the main aims of alchemists was to find a method of creating gold from other substances. A common belief of alchemists was that there is an essential substance from which all other substances formed, and that if you could reduce a substance to this original material, you could then construct it into another substance, like lead to gold. Medieval alchemists worked with two main elements or *principles*, sulphur and mercury.

Paracelsus was an alchemist and physician of the Renaissance. The Paracelsians added a third principle, salt, to make a trinity of alchemical elements.

Astronomy

The astronomy of the late Middle Ages was based on the geocentric model described by Claudius Ptolemy in antiquity. Probably very few practicing astronomers or astrologers actually read Ptolemy's *Almagest*, which had been translated into Latin by Gerard of Cremona in the 12th century. Instead they relied on introductions to the Ptolemaic system such as the *De sphaera mundi* of Johannes de Sacrobosco and the genre of textbooks known as *Theorica planetarum*. For the task of predicting planetary motions they turned to the Alfonsine tables, a set of astronomical tables based on the *Almagest* models but incorporating some later modifications, mainly the trepidation model attributed to Thabit ibn Qurra. Contrary to popular belief, astronomers of the Middle Ages and Renaissance did not resort to "epicycles on epicycles" in order to correct the original Ptolemaic models—until one comes to Copernicus himself.

Sometime around 1450, mathematician Georg Purbach (1423–1461) began a series of lectures on astronomy at the University of Vienna. Regiomontanus (1436–1476), who was then one of his students, collected his notes on the lecture and later published them as *Theoricae novae planetarum* in the 1470s. This "New *Theorica*" replaced the older *theorica* as the textbook of advanced astronomy. Purbach also began to prepare a summary and commentary on the *Almagest*. He died after completing only six books, however, and Regiomontanus continued the task, consulting a Greek manuscript brought from Constantinople by Cardinal Bessarion. When it was published in 1496, the *Epitome of the Almagest* made the highest levels of Ptolemaic astronomy widely accessible to many European astronomers for the first time.

The last major event in Renaissance astronomy is the work of Nicolaus Copernicus (1473–1543). He was among the first generation of astronomers to be trained with the *Theoricae novae* and the *Epitome*. Shortly before 1514 he began to revive Aristarchus's idea that the Earth revolves around the Sun. He spent the rest of his life attempting a mathematical proof of heliocentrism. When *De revolutionibus orbium coelestium* was finally published in 1543, Copernicus was on his deathbed. A comparison of his work with the *Almagest* shows that Copernicus was in many ways a Renaissance scientist rather than a revolutionary, because he followed Ptolemy's methods and even his order of presentation. Not until the works of Johannes Kepler (1571–1630) and Galileo Galilei (1564–1642) was Ptolemy's manner of doing astronomy superseded.

Mathematics

The accomplishments of Greek mathematicians survived throughout Late Antiquity and the Middle Ages by a long and indirect history. Much of the work of Euclid, Archimedes, and Apollonius, along with later authors such as Hero and Pappus, were copied and studied in both Byzantine culture and in Islamic centers of learning. Translations of these works began already in the 12th century, by the work of translators in Spain and Sicily working mostly from Arabic and Greek sources into Latin. Two of the most prolific were Gerard of Cremona and William of Moerbeke.

The greatest of all translation efforts, however, took place in the 15th and 16th centuries in Italy, as attested by the numerous manuscripts dating from this period currently found in European libraries. Virtually all leading mathematicians of the era were obsessed with the need for restoring the mathematical works of the ancients. Not only did humanists assist mathematicians with the retrieval of Greek manuscripts, they also took an active role in translating these work into Latin, often commissioned by religious leaders such as Nicholas V and Cardinal Bessarion.

Some of the leading figures in this effort include Regiomontanus, who made a copy of the Latin Archimedes and had a program for printing mathematical works; Commandino (1509–1575), who likewise produced an edition of Archimedes, as well as editions of works by Euclid, Hero, and Pappus; and Maurolyco (1494–1575), who not only translated the work of ancient mathematicians but added much of his own work to these. Their translations ensured that the next generation of mathematicians would be in possession of techniques far in advance of what it was generally available during the Middle Ages.

It must be borne in mind that the mathematical output of the 15th and 16th centuries was not exclusively limited to the works of the ancient Greeks. Some mathematicians, such as Tartaglia and Luca Paccioli, welcomed and expanded on the medieval traditions of both Islamic scholars and people like Jordanus and Fibonnacci.

Medicine

With the Renaissance came an increase in experimental investigation, principally in the field of dissection and body examination, thus advancing our knowledge of human anatomy. The development of modern neurology began in the 16th century with Andreas Vesalius, who described the anatomy of the brain and other organs; he had little knowledge of the brain's function, thinking that it resided mainly in the ventricles. Understanding of medical sciences and diagnosis improved, but with little direct benefit to health care. Few effective drugs existed, beyond opium and quinine. William Harvey provided a refined and complete description of the circulatory system. The most useful tomes in medicine, used both by students and expert physicians, were *materiae medicae* and *pharmacopoeiae*.

Geography and the New World

In the history of geography, the key classical text was the *Geographia* of Claudius Ptolemy (2nd century). It was translated into Latin in the 15th century by Jacopo d'Angelo. It was widely read in manuscript and went through many print editions after it was first printed in 1475. Regiomontanus worked on preparing an edition for print prior to his death; his manuscripts were consulted by later mathematicians in Nuremberg.

The information provided by Ptolemy, as well as Pliny the Elder and other classical sources, was soon seen to be in contradiction to the lands explored in the Age of Discovery. The new discoveries revealed shortcomings in classical knowledge; they also opened European imagination to new possibilities. Thomas More's *Utopia* was inspired partly by the discovery of the New World.

Chapter 13

Scientific Revolution

The **Scientific Revolution** was a series of events that marked the emergence of modern science during the early modern period, when developments in mathematics, physics, astronomy, biology (including human anatomy) and chemistry transformed the views of society about nature. The Scientific Revolution took place in Europe towards the end of the Renaissance period and continued through the late 18th century, influencing the intellectual social movement known as the Enlightenment. While its dates are debated, the publication in 1543 of Nicolaus Copernicus' *De revolutionibus orbium coelestium* (*On the Revolutions of the Heavenly Spheres*) is often cited as marking the beginning of the Scientific Revolution.

The concept of a scientific revolution taking place over an extended period emerged in the eighteenth century in the work of Jean Sylvain Bailly, who saw a two-stage process of sweeping away the old and establishing the new. The beginning of the Scientific Revolution, the 'Scientific Renaissance', was focused on the recovery of the knowledge of the ancients; this is generally considered to have ended in 1632 with publication of Galileo's *Dialogue Concerning the Two Chief World Systems*. The completion of the Scientific Revolution is attributed to the "grand synthesis" of Isaac Newton's 1687 *Principia*. The work formulated the laws of motion and universal gravitation, thereby completing the synthesis of a new cosmology. By the end of the 18th century, the Age of Enlightenment that followed the Scientific Revolution had given way to the "Age of Reflection".

Introduction

Great advances in science have been termed "revolutions" since the 18th century. In 1747, the French mathematician Alexis Clairaut wrote that "Newton was said in his own life to have created a revolution". The word was also used in the preface to Antoine Lavoisier's 1789 work announcing the discovery of oxygen. "Few revolutions in science have immediately excited so much general notice as the introduction of the theory of oxygen ... Lavoisier saw his theory accepted by all the most eminent men of his time, and established over a great part of Europe within a few years from its first promulgation."

In the 19th century, William Whewell described the revolution in science itself – the scientific method – that had taken place in the 15th-16th century. "Among the most conspicuous of the revolutions which opinions on this subject have undergone, is the transition from an implicit trust in the internal powers of man's mind to a professed dependence upon external observation; and from an unbounded reverence for the wisdom of the past, to a fervid expectation of change and improvement." This gave rise to the common view of the Scientific Revolution today:

A new view of nature emerged, replacing the Greek view that had dominated science for almost 2,000 years. Science became an autonomous discipline, distinct from both philosophy and technology and came to be regarded as having utilitarian goals.

The Scientific Revolution is traditionally assumed to start with the Copernican Revolution (initiated in 1543) and to be complete in the "grand synthesis" of Isaac Newton's 1687 *Principia*. Much of the change of attitude came from Francis Bacon whose "confident and emphatic announcement" in the modern progress of science inspired the creation of scientific societies such as the Royal Society, and Galileo who championed Copernicus and developed the science of motion.

In the 20th century, Alexandre Koyré introduced the term "scientific revolution", centering his analysis on Galileo. The term was popularized by Butterfield in his *Origins of Modern Science*. Thomas Kuhn's 1962 work *The Structure of Scientific Revolutions* emphasized that different theoretical frameworks—such as Einstein's theory of relativity and Newton's theory of gravity, which it replaced—cannot be directly compared without meaning loss.

Significance

The period saw a fundamental transformation in scientific ideas across mathematics, physics, astronomy, and biology in institutions supporting scientific investigation and in the more widely held picture of the universe. The Scientific Revolution led to the establishment of several modern sciences. In 1984, Joseph Ben-David wrote:

Rapid accumulation of knowledge, which has characterized the development of science since the 17th century, had never occurred before that time. The new kind of scientific activity emerged only in a few countries of Western Europe, and it was restricted to that small area for about two hundred years.

(Since the 19th century, scientific knowledge has been assimilated by the rest of the world).

Many contemporary writers and modern historians claim that there was a revolutionary change in world view. In 1611 the English poet, John Donne, wrote:

[The] new Philosophy calls all in doubt,

The Element of fire is quite put out;

The Sun is lost, and th'earth, and no man's wit

Can well direct him where to look for it.

Mid-20th-century historian Herbert Butterfield was less disconcerted, but nevertheless saw the change as fundamental:

Since that revolution turned the authority in English not only of the Middle Ages but of the ancient world—since it started not only in the eclipse of scholastic philosophy but in the destruction of Aristotelian physics—it outshines everything since the rise of Christianity and reduces the Renaissance and Reformation to the rank of mere episodes, mere internal displacements within the system of medieval Christendom.... [It] looms so large as the real origin both of the modern world and of the modern mentality that our customary periodization of European history has become an anachronism and an encumbrance.

The history professor Peter Harrison attributes Christianity to having contributed to the rise of the Scientific Revolution:

historians of science have long known that religious factors played a significantly positive role in the emergence and persistence of modern science in the West. Not only were many of the key figures in the rise of science individuals with sincere religious commitments, but the new approaches to nature that they pioneered were underpinned in various ways by religious assumptions. ... Yet, many of the leading figures in the scientific revolution imagined themselves to be champions of a science that was more compatible with Christianity than the medieval ideas about the natural world that they replaced.

Ancient and medieval background

The Scientific Revolution was built upon the foundation of ancient Greek learning and science in the Middle Ages, as it had been elaborated and further developed by Roman/Byzantine science and medieval Islamic science. Some scholars have noted a direct tie between "particular aspects of traditional Christianity" and the rise of science. The "Aristotelian tradition" was still an important intellectual framework in the 17th century, although by that time natural philosophers had moved away from much of it. Key scientific ideas dating back to classical antiquity had changed drastically over the years, and in many cases been discredited. The ideas that remained, which were transformed fundamentally during the Scientific Revolution, include:

- Aristotle's cosmology that placed the Earth at the center of a spherical hierarchic cosmos. The terrestrial and celestial regions were made up of different elements which had different kinds of *natural movement*.

- The terrestrial region, according to Aristotle, consisted of concentric spheres of the four elements—earth, water, air, and fire. All bodies naturally moved in straight lines until they reached the sphere appropriate to their elemental composition—their *natural place*. All other terrestrial motions were non-natural, or *violent*.
- The celestial region was made up of the fifth element, aether, which was unchanging and moved naturally with uniform circular motion. In the Aristotelian tradition, astronomical theories sought to explain the observed irregular motion of celestial objects through the combined effects of multiple uniform circular motions.
- The Ptolemaic model of planetary motion: based on the geometrical model of Eudoxus of Cnidus, Ptolemy's *Almagest*, demonstrated that calculations could compute the exact positions of the Sun, Moon, stars, and planets in the future and in the past, and showed how these computational models were derived from astronomical observations. As such they formed the model for later astronomical developments. The physical basis for Ptolemaic models invoked layers of spherical shells, though the most complex models were inconsistent with this physical explanation.

It is important to note that ancient precedent existed for alternative theories and developments which prefigured later discoveries in the area of physics and mechanics; but in light of the limited number of works to survive translation in a period when many books were lost to warfare, such developments remained obscure for centuries and are traditionally held to have had little effect on the re-discovery of such phenomena; whereas the invention of the printing press made the wide dissemination of such incremental advances of knowledge commonplace. Meanwhile, however, significant progress in geometry, mathematics, and astronomy was made in medieval times.

It is also true that many of the important figures of the Scientific Revolution shared in the general Renaissance respect for ancient learning and cited ancient pedigrees for their innovations. Nicolaus Copernicus (1473–1543), Galileo Galilei (1564–1642), Johannes Kepler (1571–1630) and Isaac Newton (1642–1727) all traced different ancient and medieval ancestries for the heliocentric system. In the Axioms Scholium of his *Principia,* Newton said its axiomatic three laws of motion were already accepted by mathematicians such as Christiaan Huygens (1629–1695), Wallace, Wren and others. While preparing a revised edition of his *Principia*, Newton attributed his law of gravity and his first law of motion to a range of historical figures.

Despite these qualifications, the standard theory of the history of the Scientific Revolution claims that the 17th century was a period of revolutionary scientific changes. Not only were there revolutionary theoretical and experimental developments, but that even more importantly, the way in which scientists worked was radically changed. For instance, although intimations of the concept of inertia are suggested sporadically in ancient discussion of motion, the salient point is that Newton's theory differed from ancient understandings in key ways, such as an external force being a requirement for violent motion in Aristotle's theory.

Scientific method

Under the scientific method as conceived in the 17th century, natural and artificial circumstances were set aside as a research tradition of systematic experimentation was slowly accepted by the scientific community. The philosophy of using an inductive approach to obtain knowledge—to abandon assumption and to attempt to observe with an open mind—was in contrast with the earlier, Aristotelian approach of deduction, by which analysis of known facts produced further understanding. In practice, many scientists and philosophers believed that a healthy mix of both was needed—the willingness to question assumptions, yet also to interpret observations assumed to have some degree of validity.

By the end of the Scientific Revolution the qualitative world of book-reading philosophers had been changed into a mechanical, mathematical world to be known through experimental research. Though it is certainly not true that Newtonian science was like modern science in all respects, it conceptually resembled ours in many ways. Many of the hallmarks of modern science, especially with regard to its institutionalization and professionalization, did not become standard until the mid-19th century.

Empiricism

The Aristotelian scientific tradition's primary mode of interacting with the world was through observation and searching for "natural" circumstances through reasoning. Coupled with this approach was the belief that rare events which seemed to contradict theoretical models were aberrations, telling nothing about nature as it "naturally" was. During the Scientific Revolution, changing perceptions about the role of the scientist in respect to nature, the value of evidence, experimental or observed, led towards a scientific methodology in which empiricism played a large, but not absolute, role.

By the start of the Scientific Revolution, empiricism had already become an important component of science and natural philosophy. Prior thinkers, including the early-14th-century nominalist philosopher William of Ockham, had begun the intellectual movement toward empiricism.

The term British empiricism came into use to describe philosophical differences perceived between two of its founders Francis Bacon, described as empiricist, and René Descartes, who was described as a rationalist. Thomas Hobbes, George Berkeley, and David Hume were the philosophy's primary exponents, who developed a sophisticated empirical tradition as the basis of human knowledge.

An influential formulation of empiricism was John Locke's *An Essay Concerning Human Understanding* (1689), in which he maintained that the only true knowledge that could be accessible to the human mind was that which was based on experience. He wrote that the human mind was created as a *tabula rasa*, a "blank tablet," upon which sensory impressions were recorded and built up knowledge through a process of reflection.

Baconian science

The philosophical underpinnings of the Scientific Revolution were laid out by Francis Bacon, who has been called the father of empiricism. His works established and popularised inductive methodologies for scientific inquiry, often called the *Baconian method*, or simply the scientific method. His demand for a planned procedure of investigating all things natural marked a new turn in the rhetorical and theoretical framework for science, much of which still surrounds conceptions of proper methodology today.

Bacon proposed a great reformation of all process of knowledge for the advancement of learning divine and human, which he called *Instauratio Magna* (The Great Instauration). For Bacon, this reformation would lead to a great advancement in science and a progeny of new inventions that would relieve mankind's miseries and needs. His *Novum Organum* was published in 1620. He argued that man is "the minister and interpreter of nature", that "knowledge and human power are synonymous", that "effects are produced by the means of instruments and helps", and that "man while operating can only apply or withdraw natural bodies; nature internally performs the rest", and later that "nature can only be commanded by obeying her". Here is an abstract of the philosophy of this work, that by the knowledge of nature and the using of instruments, man can govern or direct the natural work of nature to produce definite results. Therefore, that man, by seeking knowledge of nature, can reach power over it—and thus reestablish the "Empire of Man over creation", which had been lost by the Fall together with man's original purity. In this way, he believed, would mankind be raised above conditions of helplessness, poverty and misery, while coming into a condition of peace, prosperity and security.

For this purpose of obtaining knowledge of and power over nature, Bacon outlined in this work a new system of logic he believed to be superior to the old ways of syllogism, developing his scientific method, consisting of procedures for isolating the formal cause of a phenomenon (heat, for example) through eliminative induction. For him, the philosopher should proceed through inductive reasoning from fact to axiom to physical law. Before beginning this induction, though, the enquirer must free his or her mind from certain false notions or tendencies which distort the truth. In particular, he found that philosophy was too preoccupied with words, particularly discourse and debate, rather than actually observing the material world: "For while men believe their reason governs words, in fact, words turn back and reflect their power upon the understanding, and so render philosophy and science sophistical and inactive."

Bacon considered that it is of greatest importance to science not to keep doing intellectual discussions or seeking merely contemplative aims, but that it should work for the bettering of mankind's life by bringing forth new inventions, having even stated that "inventions are also, as it were, new creations and imitations of divine works". He explored the far-reaching and world-changing character of inventions, such as the printing press, gunpowder and the compass.

Despite his influence on scientific methodology, he himself rejected correct novel theories such as William Gilbert's magnetism, Copernicus's heliocentrism, and Kepler's laws of planetary motion.

Scientific experimentation

Bacon first described the experimental method.

There remains simple experience; which, if taken as it comes, is called accident, if sought for, experiment. The true method of experience first lights the candle [hypothesis], and then by means of the candle shows the way [arranges and delimits the experiment]; commencing as it does with experience duly ordered and digested, not bungling or erratic, and from it deducing axioms [theories], and from established axioms again new experiments.

- *—Francis Bacon. Novum Organum. 1620.*

William Gilbert was an early advocate of this method. He passionately rejected both the prevailing Aristotelian philosophy and the Scholastic method of university teaching. His book *De Magnete* was written in 1600, and he is regarded by some as the father of electricity and magnetism. In this work, he describes many of his experiments with his model Earth called the terrella. From these experiments, he concluded that the Earth was itself magnetic and that this was the reason compasses point north.

De Magnete was influential not only because of the inherent interest of its subject matter, but also for the rigorous way in which Gilbert described his experiments and his rejection of ancient theories of magnetism. According to Thomas Thomson, "Gilbert['s]... book on magnetism published in 1600, is one of the finest examples of inductive philosophy that has ever been presented to the world. It is the more remarkable, because it preceded the *Novum Organum* of Bacon, in which the inductive method of philosophizing was first explained."

Galileo Galilei has been called the "father of modern observational astronomy", the "father of modern physics", the "father of science", and "the Father of Modern Science". His original contributions to the science of motion were made through an innovative combination of experiment and mathematics.

Galileo was one of the first modern thinkers to clearly state that the laws of nature are mathematical. In *The Assayer* he wrote "Philosophy is written in this grand book, the universe ... It is written in the language of mathematics, and its characters are triangles, circles, and other geometric figures;...." His mathematical analyses are a further development of a tradition employed by late scholastic natural philosophers, which Galileo learned when he studied philosophy. He ignored Aristotelianism. In broader terms, his work marked another step towards the eventual separation of science from both philosophy and religion; a major development in human thought. He was often willing to change his views in accordance with observation. In order to perform his experiments, Galileo had to set up standards of length and time, so that measurements made on different days and in different laboratories could be compared in a reproducible fashion. This provided a reliable foundation on which to confirm mathematical laws using inductive reasoning.

Galileo showed an appreciation for the relationship between mathematics, theoretical physics, and experimental physics. He understood the parabola, both in terms of conic sections and in terms of the ordinate (y) varying as the square of the abscissa (x). Galilei further asserted that the parabola was the theoretically ideal trajectory of a uniformly accelerated projectile in the absence of friction and other disturbances. He conceded that there are limits to the validity of this theory, noting on theoretical grounds that a projectile trajectory of a size comparable to that of the Earth could not possibly be a parabola, but he nevertheless maintained that for distances up to the range of the artillery of his day, the deviation of a projectile's trajectory from a parabola would be only very slight.

Mathematization

Scientific knowledge, according to the Aristotelians, was concerned with establishing true and necessary causes of things. To the extent that medieval natural philosophers used mathematical problems, they limited social studies to theoretical analyses of local speed and other aspects of life. The actual measurement of a physical quantity, and the comparison of that measurement to a value computed on the basis of theory, was largely limited to the mathematical disciplines of astronomy and optics in Europe.

In the 16th and 17th centuries, European scientists began increasingly applying quantitative measurements to the measurement of physical phenomena on the Earth. Galileo maintained strongly that mathematics provided a kind of necessary certainty that could be compared to God's: "...with regard to those few [mathematical propositions] which the human intellect does understand, I believe its knowledge equals the Divine in objective certainty..."

Galileo anticipates the concept of a systematic mathematical interpretation of the world in his book *Il Saggiatore*:

Philosophy [i.e., physics] is written in this grand book—I mean the universe—which stands continually open to our gaze, but it cannot be understood unless one first learns to comprehend the language and interpret the characters in which it is written. It is written in the language of mathematics, and its characters are triangles, circles, and other geometrical figures, without which it is humanly impossible to understand a single word of it; without these, one is wandering around in a dark labyrinth.

The mechanical philosophy

Aristotle recognized four kinds of causes, and where applicable, the most important of them is the "final cause". The final cause was the aim, goal, or purpose of some natural process or man-made thing. Until the Scientific Revolution, it was very natural to see such aims, such as a child's growth, for example, leading to a mature adult. Intelligence was assumed only in the purpose of man-made artifacts; it was not attributed to other animals or to nature.

In "mechanical philosophy" no field or action at a distance is permitted, particles or corpuscles of matter are fundamentally inert. Motion is caused by direct physical collision. Where natural substances had previously been understood organically, the mechanical philosophers viewed them as machines. As a result, Isaac Newton's theory seemed like some kind of throwback to "spooky action at a distance". According to Thomas Kuhn, Newton and Descartes held the teleological principle that God conserved the amount of motion in the universe:

Gravity, interpreted as an innate attraction between every pair of particles of matter, was an occult quality in the same sense as the scholastics' "tendency to fall" had been.... By the mid eighteenth century that interpretation had been almost universally accepted, and the result was a genuine reversion (which is not the same as a retrogression) to a scholastic standard. Innate attractions and repulsions joined size, shape, position and motion as physically irreducible primary properties of matter.

Newton had also specifically attributed the inherent power of inertia to matter, against the mechanist thesis that matter has no inherent powers. But whereas Newton vehemently denied gravity was an inherent power of matter, his collaborator Roger Cotes made gravity also an inherent power of matter, as set out in his famous preface to the *Principia's* 1713 second edition which he edited, and contradicted Newton himself. And it was Cotes's interpretation of gravity rather than Newton's that came to be accepted.

Institutionalization

The first moves towards the institutionalization of scientific investigation and dissemination took the form of the establishment of societies, where new discoveries were aired, discussed and published. The first scientific society to be established was the Royal Society of London. This grew out of an earlier group, centred around Gresham College in the 1640s and 1650s. According to a history of the College:

The scientific network which centred on Gresham College played a crucial part in the meetings which led to the formation of the Royal Society.

These physicians and natural philosophers were influenced by the "new science", as promoted by Francis Bacon in his *New Atlantis*, from approximately 1645 onwards. A group known as *The Philosophical Society of Oxford* was run under a set of rules still retained by the Bodleian Library.

On 28 November 1660, the 1660 committee of 12 announced the formation of a "College for the Promoting of Physico-Mathematical Experimental Learning", which would meet weekly to discuss science and run experiments. At the second meeting, Robert Moray announced that the King approved of the gatherings, and a Royal charter was signed on 15 July 1662 creating the "Royal Society of London", with Lord Brouncker serving as the first President. A second Royal Charter was signed on 23 April 1663, with the King noted as the Founder and with the name of "the Royal Society of London for the Improvement of Natural Knowledge"; Robert Hooke was appointed as Curator of Experiments in November. This initial royal favour has continued, and since then every monarch has been the patron of the Society.

The Society's first Secretary was Henry Oldenburg. Its early meetings included experiments performed first by Robert Hooke and then by Denis Papin, who was appointed in 1684. These experiments varied in their subject area, and were both important in some cases and trivial in others. The society began publication of *Philosophical Transactions* from 1665, the oldest and longest-running scientific journal in the world, which established the important principles of scientific priority and peer review.

The French established the Academy of Sciences in 1666. In contrast to the private origins of its British counterpart, the Academy was founded as a government body by Jean-Baptiste Colbert. Its rules were set down in 1699 by King Louis XIV, when it received the name of 'Royal Academy of Sciences' and was installed in the Louvre in Paris.

New ideas

As the Scientific Revolution was not marked by any single change, the following new ideas contributed to what is called the Scientific Revolution. Many of them were revolutions in their own fields.

Astronomy

- Heliocentrism

For almost five millennia, the geocentric model of the Earth as the center of the universe had been accepted by all but a few astronomers. In Aristotle's cosmology, Earth's central location was perhaps less significant than its identification as a realm of imperfection, inconstancy, irregularity and change, as opposed to the "heavens" (Moon, Sun, planets, stars), which were regarded as perfect, permanent, unchangeable, and in religious thought, the realm of heavenly beings. The Earth was even composed of different material, the four elements "earth", "water", "fire", and "air", while sufficiently far above its surface (roughly the Moon's orbit), the heavens were composed of a different substance called "aether". The heliocentric model that replaced it involved not only the radical displacement of the earth to an orbit around the sun, but its sharing a placement with the other planets implied a universe of heavenly components made from the same changeable substances as the Earth. Heavenly motions no longer needed to be governed by a theoretical perfection, confined to circular orbits.

Copernicus' 1543 work on the heliocentric model of the solar system tried to demonstrate that the sun was the center of the universe. Few were bothered by this suggestion, and the pope and several archbishops were interested enough by it to want more detail. His model was later used to create the calendar of Pope Gregory XIII. However, the idea that the earth moved around the sun was doubted by most of Copernicus' contemporaries. It contradicted not only empirical observation, due to the absence of an observable stellar parallax, but more significantly at the time, the authority of Aristotle.

The discoveries of Johannes Kepler and Galileo gave the theory credibility. Kepler was an astronomer who, using the accurate observations of Tycho Brahe, proposed that the planets move around the sun not in circular orbits, but in elliptical ones. Together with his other laws of planetary motion, this allowed him to create a model of the solar system that was an improvement over Copernicus' original system. Galileo's main contributions to the acceptance of the heliocentric system were his mechanics, the observations he made with his telescope, as well as his detailed presentation of the case for the system. Using an early theory of inertia, Galileo could explain why rocks dropped from a tower fall straight down even if the earth rotates. His observations of the moons of Jupiter, the phases of Venus, the spots on the sun, and mountains on the moon all helped to discredit the Aristotelian philosophy and the Ptolemaic theory of the solar system. Through their combined discoveries, the heliocentric system gained support, and at the end of the 17th century it was generally accepted by astronomers.

This work culminated in the work of Isaac Newton. Newton's *Principia* formulated the laws of motion and universal gravitation, which dominated scientists' view of the physical universe for the next three centuries. By deriving Kepler's laws of planetary motion from his mathematical description of gravity, and then using the same principles to account for the trajectories of comets, the tides, the precession of the equinoxes, and other phenomena, Newton removed the last doubts about the validity of the heliocentric model of the cosmos. This work also demonstrated that the motion of objects on Earth and of celestial bodies could be described by the same principles. His prediction that the Earth should be shaped as an oblate spheroid was later vindicated by other scientists. His laws of motion were to be the solid foundation of mechanics; his law of universal gravitation combined terrestrial and celestial mechanics into one great system that seemed to be able to describe the whole world in mathematical formulae.

- Gravitation

As well as proving the heliocentric model, Newton also developed the theory of gravitation. In 1679, Newton began to consider gravitation and its effect on the orbits of planets with reference to Kepler's laws of planetary motion. This followed stimulation by a brief exchange of letters in 1679–80 with Robert Hooke, who had been appointed to manage the Royal Society's correspondence, and who opened a correspondence intended to elicit contributions from Newton to Royal Society transactions. Newton's reawakening interest in astronomical matters received further stimulus by the appearance of a comet in the winter of 1680–1681, on which he corresponded with John Flamsteed. After the exchanges with Hooke, Newton worked out proof that the elliptical form of planetary orbits would result from a centripetal force inversely proportional to the square of the radius vector (see Newton's law of universal gravitation – History and *De motu corporum in gyrum*). Newton communicated his results to Edmond Halley and to the Royal Society in *De motu corporum in gyrum*, in 1684. This tract contained the nucleus that Newton developed and expanded to form the *Principia*.

The *Principia* was published on 5 July 1687 with encouragement and financial help from Edmond Halley. In this work, Newton stated the three universal laws of motion that contributed to many advances during the Industrial Revolution which soon followed and were not to be improved upon for more than 200 years. Many of these advancements continue to be the underpinnings of non-relativistic technologies in the modern world. He used the Latin word *gravitas* (weight) for the effect that would become known as gravity, and defined the law of universal gravitation.

Newton's postulate of an invisible force able to act over vast distances led to him being criticised for introducing "occult agencies" into science. Later, in the second edition of the *Principia* (1713), Newton firmly rejected such criticisms in a concluding General Scholium, writing that it was enough that the phenomena implied a gravitational attraction, as they did; but they did not so far indicate its cause, and it was both unnecessary and improper to frame hypotheses of things that were not implied by the phenomena. (Here Newton used what became his famous expression "hypotheses non fingo").

Biology and medicine

- Medical discoveries

The writings of Greek physician Galen had dominated European medical thinking for over a millennium. The Flemish scholar Vesalius demonstrated mistakes in Galen's ideas. Vesalius dissected human corpses, whereas Galen dissected animal corpses. Published in 1543, Vesalius' *De humani corporis fabrica* was a groundbreaking work of human anatomy. It emphasized the priority of dissection and what has come to be called the "anatomical" view of the body, seeing human internal functioning as an essentially corporeal structure filled with organs arranged in three-dimensional space. This was in stark contrast to many of the anatomical models used previously, which had strong Galenic/Aristotelean elements, as well as elements of astrology.

Besides the first good description of the sphenoid bone, he showed that the sternum consists of three portions and the sacrum of five or six; and described accurately the vestibule in the interior of the temporal bone. He not only verified the observation of Etienne on the valves of the hepatic veins, but he described the vena azygos, and discovered the canal which passes in the fetus between the umbilical vein and the vena cava, since named ductus venosus. He described the omentum, and its connections with the stomach, the spleen and the colon; gave the first correct views of the structure of the pylorus; observed the small size of the caecal appendix in man; gave the first good account of the mediastinum and pleura and the fullest description of the anatomy of the brain yet advanced. He did not understand the inferior recesses; and his account of the nerves is confused by regarding the optic as the first pair, the third as the fifth and the fifth as the seventh.

Before Vesalius, the anatomical notes by Alessandro Achillini demonstrate a detailed description of the human body and compares what he has found during his dissections to what others like Galen and Avicenna have found and notes their similarities and differences. Niccolò Massa was an Italian anatomist who wrote an early anatomy text *Anatomiae Libri Introductorius* in 1536, described the cerebrospinal fluid and was the author of several medical works. Jean Fernel was a French physician who introduced the term "physiology" to describe the study of the body's function and was the first person to describe the spinal canal.

Further groundbreaking work was carried out by William Harvey, who published *De Motu Cordis* in 1628. Harvey made a detailed analysis of the overall structure of the heart, going on to an analysis of the arteries, showing how their pulsation depends upon the contraction of the left ventricle, while the contraction of the right ventricle propels its charge of blood into the pulmonary artery. He noticed that the two ventricles move together almost simultaneously and not independently like had been thought previously by his predecessors.

In the eighth chapter, Harvey estimated the capacity of the heart, how much blood is expelled through each pump of the heart, and the number of times the heart beats in half an hour. From these estimations, he demonstrated that according to Gaelen's theory that blood was continually produced in the liver, the absurdly large figure of 540 pounds of blood would have to be produced every day. Having this simple mathematical proportion at hand—which would imply a seemingly impossible role for the liver—Harvey went on to demonstrate how the blood circulated in a circle by means of countless experiments initially done on serpents and fish: tying their veins and arteries in separate periods of time, Harvey noticed the modifications which occurred; indeed, as he tied the veins, the heart would become empty, while as he did the same to the arteries, the organ would swell up.

This process was later performed on the human body (in the image on the left): the physician tied a tight ligature onto the upper arm of a person. This would cut off blood flow from the arteries and the veins. When this was done, the arm below the ligature was cool and pale, while above the ligature it was warm and swollen. The ligature was loosened slightly, which allowed blood from the arteries to come into the arm, since arteries are deeper in the flesh than the veins. When this was done, the opposite effect was seen in the lower arm. It was now warm and swollen. The veins were also more visible, since now they were full of blood.

Various other advances in medical understanding and practice were made. French physician Pierre Fauchard started dentistry science as we know it today, and he has been named "the father of modern dentistry". Surgeon Ambroise Paré (c. 1510–1590) was a leader in surgical techniques and battlefield medicine, especially the treatment of wounds, and Herman Boerhaave (1668–1738) is sometimes referred to as a "father of physiology" due to his exemplary teaching in Leiden and his textbook *Institutiones medicae* (1708).

Chemistry

Chemistry, and its antecedent alchemy, became an increasingly important aspect of scientific thought in the course of the 16th and 17th centuries. The importance of chemistry is indicated by the range of important scholars who actively engaged in chemical research. Among them were the astronomer Tycho Brahe, the chemical physician Paracelsus, Robert Boyle, Thomas Browne and Isaac Newton. Unlike the mechanical philosophy, the chemical philosophy stressed the active powers of matter, which alchemists frequently expressed in terms of vital or active principles—of spirits operating in nature.

Practical attempts to improve the refining of ores and their extraction to smelt metals were an important source of information for early chemists in the 16th century, among them Georg Agricola (1494–1555), who published his great work *De re metallica* in 1556. His work describes the highly developed and complex processes of mining metal ores, metal extraction and metallurgy of the time. His approach removed the mysticism associated with the subject, creating the practical base upon which others could build.

English chemist Robert Boyle (1627–1691) is considered to have refined the modern scientific method for alchemy and to have separated chemistry further from alchemy. Although his research clearly has its roots in the alchemical tradition, Boyle is largely regarded today as the first modern chemist, and therefore one of the founders of modern chemistry, and one of the pioneers of modern experimental scientific method. Although Boyle was not the original discover, he is best known for Boyle's law, which he presented in 1662: the law describes the inversely proportional relationship between the absolute pressure and volume of a gas, if the temperature is kept constant within a closed system.

Boyle is also credited for his landmark publication *The Sceptical Chymist* in 1661, which is seen as a cornerstone book in the field of chemistry. In the work, Boyle presents his hypothesis that every phenomenon was the result of collisions of particles in motion. Boyle appealed to chemists to experiment and asserted that experiments denied the limiting of chemical elements to only the classic four: earth, fire, air, and water. He also pleaded that chemistry should cease to be subservient to medicine or to alchemy, and rise to the status of a science. Importantly, he advocated a rigorous approach to scientific experiment: he believed all theories must be tested experimentally before being regarded as true. The work contains some of the earliest modern ideas of atoms, molecules, and chemical reaction, and marks the beginning of the history of modern chemistry.

Physical

- Optics

Important work was done in the field of optics. Johannes Kepler published *Astronomiae Pars Optica* (*The Optical Part of Astronomy*) in 1604. In it, he described the inverse-square law governing the intensity of light, reflection by flat and curved mirrors, and principles of pinhole cameras, as well as the astronomical implications of optics such as parallax and the apparent sizes of heavenly bodies. *Astronomiae Pars Optica* is generally recognized as the foundation of modern optics (though the law of refraction is conspicuously absent).

Willebrord Snellius (1580–1626) found the mathematical law of refraction, now known as Snell's law, in 1621. It had been published earlier in 984 A. D. by Ibn Sahl. Subsequently René Descartes (1596–1650) showed, by using geometric construction and the law of refraction (also known as Descartes' law), that the angular radius of a rainbow is 42° (i.e. the angle subtended at the eye by the edge of the rainbow and the rainbow's centre is 42°). He also independently discovered the law of reflection, and his essay on optics was the first published mention of this law.

Christiaan Huygens (1629–1695) wrote several works in the area of optics. These included the *Opera reliqua* (also known as

Christiani Hugenii Zuilichemii, dum viveret Zelhemii toparchae, opuscula posthuma) and the *Traité de la lumière*.

Isaac Newton investigated the refraction of light, demonstrating that a prism could decompose white light into a spectrum of colours, and that a lens and a second prism could recompose the multicoloured spectrum into white light. He also showed that the coloured light does not change its properties by separating out a coloured beam and shining it on various objects. Newton noted that regardless of whether it was reflected or scattered or transmitted, it stayed the same colour. Thus, he observed that colour is the result of objects interacting with already-coloured light rather than objects generating the colour themselves. This is known as Newton's theory of colour. From this work he concluded that any refracting telescope would suffer from the dispersion of light into colours. The interest of the Royal Society encouraged him to publish his notes *On Colour* (later expanded into *Opticks*). Newton argued that light is composed of particles or *corpuscles* and were refracted by accelerating toward the denser medium, but he had to associate them with waves to explain the diffraction of light.

In his *Hypothesis of Light* of 1675, Newton posited the existence of the ether to transmit forces between particles. In 1704, Newton published *Opticks*, in which he expounded his corpuscular theory of light. He considered light to be made up of extremely subtle corpuscles, that ordinary matter was made of grosser corpuscles and speculated that through a kind of alchemical transmutation "Are not gross Bodies and Light convertible into one another, ...and may not Bodies receive much of their Activity from the Particles of Light which enter their Composition?"

- Electricity

Dr. William Gilbert, in *De Magnete*, invented the New Latin word *electricus* from *ἤλεκτρον* (*elektron*), the Greek word for "amber". Gilbert undertook a number of careful electrical experiments, in the course of which he discovered that many substances other than amber, such as sulphur, wax, glass, etc., were capable of manifesting electrical properties. Gilbert also discovered that a heated body lost its electricity and that moisture prevented the electrification of all bodies, due to the now well-known fact that moisture impaired the insulation of such bodies. He also noticed that electrified substances attracted all other substances indiscriminately, whereas a magnet only attracted iron. The many discoveries of this nature earned for Gilbert the title of *founder of the electrical science*. By investigating the forces on a light metallic needle, balanced on a point, he extended the list of electric bodies, and found also that many substances, including metals and natural magnets, showed no attractive forces when rubbed. He noticed that dry weather with north or east wind was the most favourable atmospheric condition for exhibiting electric phenomena—an observation liable to misconception until the difference between conductor and insulator was understood.

Robert Boyle also worked frequently at the new science of electricity, and added several substances to Gilbert's list of electrics. He left a detailed account of his researches under the title of *Experiments on the Origin of Electricity*. Boyle, in 1675, stated that electric attraction and repulsion can act across a vacuum. One of his important discoveries was that electrified bodies in a vacuum would attract light substances, this indicating that the electrical effect did not depend upon the air as a medium. He also added resin to the then known list of electrics.

This was followed in 1660 by Otto von Guericke, who invented an early electrostatic generator. By the end of the 17th century, researchers had developed practical means of generating electricity by friction with an electrostatic generator, but the development of electrostatic machines did not begin in earnest until the 18th century, when they became fundamental instruments in the studies about the new science of electricity. The first usage of the word *electricity* is ascribed to Sir Thomas Browne in his 1646 work, *Pseudodoxia Epidemica*. In 1729 Stephen Gray (1666–1736) demonstrated that electricity could be "transmitted" through metal filaments.

New mechanical devices

As an aid to scientific investigation, various tools, measuring aids and calculating devices were developed in this period.

Calculating devices

John Napier introduced logarithms as a powerful mathematical tool. With the help of the prominent mathematician Henry Briggs their logarithmic tables embodied a computational advance that made calculations by hand much quicker. His Napier's bones used a set of numbered rods as a multiplication tool using the system of lattice multiplication. The way was opened to later scientific advances, particularly in astronomy and dynamics.

At Oxford University, Edmund Gunter built the first analog device to aid computation. The 'Gunter's scale' was a large plane scale, engraved with various scales, or lines. Natural lines, such as the line of chords, the line of sines and tangents are placed on one side of the scale and the corresponding artificial or logarithmic ones were on the other side. This calculating aid was a predecessor of the slide rule. It was William Oughtred (1575–1660) who first used two such scales sliding by one another to perform direct multiplication and division, and thus is credited as the inventor of the slide rule in 1622.

Blaise Pascal (1623–1662) invented the mechanical calculator in 1642. The introduction of his Pascaline in 1645 launched the development of mechanical calculators first in Europe and then all over the world. Gottfried Leibniz (1646–1716), building on Pascal's work, became one of the most prolific inventors in the field of mechanical calculators; he was the first to describe a pinwheel calculator, in 1685, and invented the Leibniz wheel, used in the arithmometer, the first mass-produced mechanical calculator. He also refined the binary number system, foundation of virtually all modern computer architectures.

John Hadley (1682–1744) was the inventor of the octant, the precursor to the sextant (invented by John Bird), which greatly improved the science of navigation.

Industrial machines

Denis Papin (1647–c.1712) was best known for his pioneering invention of the steam digester, the forerunner of the steam engine. The first working steam engine was patented in 1698 by the English inventor Thomas Savery, as a "...new invention for raising of water and occasioning motion to all sorts of mill work by the impellent force of fire, which will be of great use and advantage for drayning mines, serveing townes with water, and for the working of all sorts of mills where they have not the benefitt of water nor constant windes." [*sic*] The invention was demonstrated to the Royal Society on 14 June 1699 and the machine was described by Savery in his book *The Miner's Friend; or, An Engine to Raise Water by Fire* (1702), in which he claimed that it could pump water out of mines. Thomas Newcomen (1664–1729) perfected the practical steam engine for pumping water, the Newcomen steam engine. Consequently, Thomas Newcomen can be regarded as a forefather of the Industrial Revolution. Abraham Darby I (1678–1717) was the first, and most famous, of three generations of the Darby family who played an important role in the Industrial Revolution. He developed a method of producing high-grade iron in a blast furnace fueled by coke rather than charcoal. This was a major step forward in the production of iron as a raw material for the Industrial Revolution.

Telescopes

Refracting telescopes first appeared in the Netherlands in 1608, apparently the product of spectacle makers experimenting with lenses. The inventor is unknown but Hans

Lippershey applied for the first patent, followed by Jacob Metius of Alkmaar. Galileo was one of the first scientists to use this new tool for his astronomical observations in 1609.

The reflecting telescope was described by James Gregory in his book *Optica Promota* (1663). He argued that a mirror shaped like the part of a conic section, would correct the spherical aberration that flawed the accuracy of refracting telescopes. His design, the "Gregorian telescope", however, remained un-built.

In 1666, Isaac Newton argued that the faults of the refracting telescope were fundamental because the lens refracted light of different colors differently. He concluded that light could not be refracted through a lens without causing chromatic aberrations. From these experiments Newton concluded that no improvement could be made in the refracting telescope. However, he was able to demonstrate that the angle of reflection remained the same for all colors, so he decided to build a reflecting telescope. It was completed in 1668 and is the earliest known functional reflecting telescope.

50 years later, John Hadley developed ways to make precision aspheric and parabolic objective mirrors for reflecting telescopes, building the first parabolic Newtonian telescope and a Gregorian telescope with accurately shaped mirrors. These were successfully demonstrated to the Royal Society.

Other devices

The invention of the vacuum pump paved the way for the experiments of Robert Boyle and Robert Hooke into the nature of vacuum and atmospheric pressure. The first such device was made by Otto von Guericke in 1654. It consisted of a piston and an air gun cylinder with flaps that could suck the air from any vessel that it was connected to. In 1657, he pumped the air out of two conjoined hemispheres and demonstrated that a team of sixteen horses were incapable of pulling it apart. The air pump construction was greatly improved by Robert Hooke in 1658.

Evangelista Torricelli (1607–1647) was best known for his invention of the mercury barometer. The motivation for the invention was to improve on the suction pumps that were used to raise water out of the mines. Torricelli constructed a sealed tube filled with mercury, set vertically into a basin of the same substance. The column of mercury fell downwards, leaving a Torricellian vacuum above.

Materials, construction, and aesthetics

Surviving instruments from this period, tend to be made of durable metals such as brass, gold, or steel, although examples such as telescopes made of wood, pasteboard, or with leather components exist. Those instruments that exist in collections today tend to be robust examples, made by skilled craftspeople for and at the expense of wealthy patrons. These may have been commissioned as displays of wealth. In addition, the instruments preserved in collections may not have received heavy use in scientific work; instruments that had visibly received heavy use were typically destroyed, deemed unfit for display, or excluded from collections altogether. It is also postulated that the scientific instruments preserved in many collections were chosen because they were more appealing to collectors, by virtue of being more ornate, more portable, or made with higher-grade materials.

Intact air pumps are particularly rare. The pump at right included a glass sphere to permit demonstrations inside the vacuum chamber, a common use. The base was wooden, and the cylindrical pump was brass. Other vacuum chambers that survived were made of brass hemispheres.

Instrument makers of the late seventeenth and early eighteenth century were commissioned by organizations seeking help with navigation, surveying, warfare, and astronomical observation. The increase in uses for such instruments, and their widespread use in global exploration and conflict, created a need for new methods of manufacture and repair, which would be met by the Industrial Revolution.

Scientific developments

People and key ideas that emerged from the 16th and 17th centuries:

- First printed edition of Euclid's *Elements* in 1482.
- Nicolaus Copernicus (1473–1543) published *On the Revolutions of the Heavenly Spheres* in 1543, which advanced the heliocentric theory of cosmology.
- Andreas Vesalius (1514–1564) published *De Humani Corporis Fabrica* (*On the Structure of the Human Body*) (1543), which discredited Galen's views. He found that the circulation of blood resolved from

pumping of the heart. He also assembled the first human skeleton from cutting open cadavers.

- The French mathematician François Viète (1540–1603) published *In Artem Analyticem Isagoge* (1591), which gave the first symbolic notation of parameters in literal algebra.
- William Gilbert (1544–1603) published *On the Magnet and Magnetic Bodies, and on the Great Magnet the Earth* in 1600, which laid the foundations of a theory of magnetism and electricity.
- Tycho Brahe (1546–1601) made extensive and more accurate naked eye observations of the planets in the late 16th century. These became the basic data for Kepler's studies.
- Sir Francis Bacon (1561–1626) published *Novum Organum* in 1620, which outlined a new system of logic based on the process of reduction, which he offered as an improvement over Aristotle's philosophical process of syllogism. This contributed to the development of what became known as the scientific method.
- Galileo Galilei (1564–1642) improved the telescope, with which he made several important astronomical observations, including the four largest moons of Jupiter (1610), the phases of Venus (1610 – proving Copernicus correct), the rings of Saturn (1610), and made detailed observations of sunspots. He developed the laws for falling bodies based on pioneering quantitative experiments which he analyzed mathematically.
- Johannes Kepler (1571–1630) published the first two of his three laws of planetary motion in 1609.

- William Harvey (1578–1657) demonstrated that blood circulates, using dissections and other experimental techniques.
- René Descartes (1596–1650) published his *Discourse on the Method* in 1637, which helped to establish the scientific method.
- Antonie van Leeuwenhoek (1632–1723) constructed powerful single lens microscopes and made extensive observations that he published around 1660, opening up the micro-world of biology.
- Christiaan Huygens (1629–1695) published major studies of mechanics (he was the first one to correctly formulate laws concerning centrifugal force and discovered the theory of the pendulum) and optics (being one of the most influential proponents of the wave theory of light).
- Isaac Newton (1643–1727) built upon the work of Kepler, Galileo and Huygens. He showed that an inverse square law for gravity explained the elliptical orbits of the planets, and advanced the law of universal gravitation. His development of infinitesimal calculus (along with Leibniz) opened up new applications of the methods of mathematics to science. Newton taught that scientific theory should be coupled with rigorous experimentation, which became the keystone of modern science.

Criticism

The idea that modern science took place as a kind of revolution has been debated among historians. A weakness of the idea of a scientific revolution is the lack of a systematic approach to the question of knowledge in the period comprehended between the 14th and 17th centuries, leading to misunderstandings on the value and role of modern authors. From this standpoint, the continuity thesis is the hypothesis that there was no radical discontinuity between the intellectual development of the Middle Ages and the developments in the Renaissance and early modern period and has been deeply and widely documented by the works of scholars like Pierre Duhem, John Hermann Randall, Alistair Crombie and William A. Wallace, who proved the preexistence of a wide range of ideas used by the followers of the Scientific Revolution thesis to substantiate their claims. Thus, the idea of a scientific revolution following the Renaissance is—according to the continuity thesis—a myth. Some continuity theorists point to earlier intellectual revolutions occurring in the Middle Ages, usually referring to either a European Renaissance of the 12th century or a medieval Muslim scientific revolution, as a sign of continuity.

Another contrary view has been recently proposed by Arun Bala in his dialogical history of the birth of modern science. Bala proposes that the changes involved in the Scientific Revolution—the mathematical realist turn, the mechanical philosophy, the atomism, the central role assigned to the Sun in Copernican heliocentrism—have to be seen as rooted in multicultural influences on Europe. He sees specific influences in Alhazen's physical optical theory, Chinese mechanical technologies leading to the perception of the world as a machine, the Hindu-Arabic numeral system, which carried implicitly a new mode of mathematical atomic thinking, and the heliocentrism rooted in ancient Egyptian religious ideas associated with Hermeticism.

Bala argues that by ignoring such multicultural impacts we have been led to a Eurocentric conception of the Scientific Revolution. However, he clearly states: "The makers of the revolution—Copernicus, Kepler, Galileo, Descartes, Newton, and many others—had to selectively appropriate relevant ideas, transform them, and create new auxiliary concepts in order to complete their task... In the ultimate analysis, even if the revolution was rooted upon a multicultural base it is the accomplishment of Europeans in Europe." Critics note that lacking documentary evidence of transmission of specific scientific ideas, Bala's model will remain "a working hypothesis, not a conclusion".

A third approach takes the term "Renaissance" literally as a "rebirth". A closer study of Greek philosophy and Greek mathematics demonstrates that nearly all of the so-called revolutionary results of the so-called scientific revolution were in actuality restatements of ideas that were in many cases older than those of Aristotle and in nearly all cases at least as old as Archimedes. Aristotle even explicitly argues against some of the ideas that were espoused during the Scientific Revolution, such as heliocentrism. The basic ideas of the scientific method were well known to Archimedes and his contemporaries, as demonstrated in the well-known discovery of buoyancy. Atomism was first thought of by Leucippus and Democritus. Lucio Russo claims that science as a unique approach to objective knowledge was born in the Hellenistic period (c. 300 BC), but was extinguished with the advent of the Roman Empire. This approach to the Scientific Revolution reduces it to a period of relearning classical ideas that is very much an extension of the Renaissance. This view does not deny that a change occurred but argues that it was a reassertion of previous knowledge (a renaissance) and not the creation of new knowledge. It cites statements from Newton, Copernicus and others in favour of the Pythagorean worldview as evidence.

In more recent analysis of the Scientific Revolution during this period, there has been criticism of not only the Eurocentric ideologies spread, but also of the dominance of male scientists of the time. Female scholars were not always given the opportunities that a male scholar would have had, and the incorporation of women's work in the sciences during this time tends to be obscured. Scholars have tried to look into the participation of women in the 17th century in science, and even with sciences as simple as domestic knowledge women were making advances. With the limited history provided from texts of the period we are not completely aware if women were helping these scientists develop the ideas they did. Another idea to consider is the way this period influenced even the women scientists of the periods following it. Annie Jump Cannon was an astronomer who benefitted from the laws and theories developed from this period; she made several advances in the century following the Scientific Revolution. It was an important period for the future of science, including the incorporation of women into fields using the developments made.

Chapter 14

History of Natural Science

Some scholars trace the origins of natural science as far back as pre-literate human societies, where understanding the natural world was necessary for survival. People observed and built up knowledge about the behavior of animals and the usefulness of plants as food and medicine, which was passed down from generation to generation. These primitive understandings gave way to more formalized inquiry around 3500 to 3000 BC in the Mesopotamian and Ancient Egyptian cultures, which produced the first known written evidence of natural philosophy, the precursor of natural science. While the writings show an interest in astronomy, mathematics and other aspects of the physical world, the ultimate aim of inquiry about nature's workings was in all cases religious or mythological, not scientific.

A tradition of scientific inquiry also emerged in Ancient China, where Taoist alchemists and philosophers experimented with elixirs to extend life and cure ailments. They focused on the yin and yang, or contrasting elements in nature; the yin was associated with femininity and coldness, while yang was associated with masculinity and warmth. The five phases – fire, earth, metal, wood, and water – described a cycle of transformations in nature. Water turned into wood, which turned into fire when it burned. The ashes left by fire were earth. Using these principles, Chinese philosophers and doctors explored human anatomy, characterizing organs as predominantly yin or yang and understood the relationship between the pulse, the heart and the flow of blood in the body centuries before it became accepted in the West.

Little evidence survives of how Ancient Indian cultures around the Indus River understood nature, but some of their perspectives may be reflected in the Vedas, a set of sacred Hindu texts. They reveal a conception of the universe as ever-expanding and constantly being recycled and reformed. Surgeons in the Ayurvedic tradition saw health and illness as a combination of three humors: wind, bile and phlegm. A healthy life was the result of a balance among these humors. In Ayurvedic thought, the body consisted of five elements: earth, water, fire, wind, and empty space. Ayurvedic surgeons performed complex surgeries and developed a detailed understanding of human anatomy.

Pre-Socratic philosophers in Ancient Greek culture brought natural philosophy a step closer to direct inquiry about cause and effect in nature between 600 and 400 BC, although an element of magic and mythology remained. Natural phenomena such as earthquakes and eclipses were explained increasingly in the context of nature itself instead of being attributed to angry gods. Thales of Miletus, an early philosopher who lived from 625 to 546 BC, explained earthquakes by theorizing that the world floated on water and that water was the fundamental element in nature. In the 5th century BC, Leucippus was an early exponent of atomism, the idea that the world is made up of fundamental indivisible particles. Pythagoras applied Greek innovations in mathematics to astronomy, and suggested that the earth was spherical.

Aristotelian natural philosophy (400 BC–1100 AD)

- Later Socratic and Platonic thought focused on ethics, morals and art and did not attempt an investigation of the physical world; Plato criticized pre-Socratic thinkers as materialists and anti-religionists. Aristotle, however, a student of Plato who lived from 384 to 322 BC, paid closer attention to the natural world in his philosophy. In his *History of Animals*, he described the inner workings of 110 species, including the stingray, catfish and bee. He investigated chick embryos by breaking open eggs and observing them at various stages of development. Aristotle's works were influential through the 16th century, and he is considered to be the father of biology for his pioneering work in that science. He also presented philosophies about physics, nature, and astronomy using inductive reasoning in his works *Physics* and *Meteorology*.

While Aristotle considered natural philosophy more seriously than his predecessors, he approached it as a theoretical branch of science. Still, inspired by his work, Ancient Roman philosophers of the early 1st century AD, including Lucretius, Seneca and Pliny the Elder, wrote treatises that dealt with the rules of the natural world in varying degrees of depth. Many Ancient Roman Neoplatonists of the 3rd to the 6th centuries also adapted Aristotle's teachings on the physical world to a philosophy that emphasized spiritualism. Early medieval philosophers including Macrobius, Calcidius and Martianus

Capella also examined the physical world, largely from a cosmological and cosmographical perspective, putting forth theories on the arrangement of celestial bodies and the heavens, which were posited as being composed of aether.

Aristotle's works on natural philosophy continued to be translated and studied amid the rise of the Byzantine Empire and Abbasid Caliphate.

In the Byzantine Empire, John Philoponus, an Alexandrian Aristotelian commentator and Christian theologian was the first who questioned Aristotle's teaching of physics. Unlike Aristotle who based his physics on verbal argument, Philoponus instead relied on observation and argued for observation rather than resorting into verbal argument. He introduced the theory of impetus. John Philoponus' criticism of Aristotelian principles of physics served as inspiration for Galileo Galilei during the Scientific Revolution.

A revival in mathematics and science took place during the time of the Abbasid Caliphate from the 9th century onward, when Muslim scholars expanded upon Greek and Indian natural philosophy. The words *alcohol*, *algebra* and *zenith* all have Arabic roots.

Medieval natural philosophy (1100–1600)

Aristotle's works and other Greek natural philosophy did not reach the West until about the middle of the 12th century, when works were translated from Greek and Arabic into Latin. The development of European civilization later in the Middle Ages brought with it further advances in natural philosophy.

European inventions such as the horseshoe, horse collar and crop rotation allowed for rapid population growth, eventually giving way to urbanization and the foundation of schools connected to monasteries and cathedrals in modern-day France and England. Aided by the schools, an approach to Christian theology developed that sought to answer questions about nature and other subjects using logic. This approach, however, was seen by some detractors as heresy. By the 12th century, Western European scholars and philosophers came into contact with a body of knowledge of which they had previously been ignorant: a large corpus of works in Greek and Arabic that were preserved by Islamic scholars. Through translation into Latin, Western Europe was introduced to Aristotle and his natural philosophy. These works were taught at new universities in Paris and Oxford by the early 13th century, although the practice was frowned upon by the Catholic church. A 1210 decree from the Synod of Paris ordered that "no lectures are to be held in Paris either publicly or privately using Aristotle's books on natural philosophy or the commentaries, and we forbid all this under pain of excommunication."

In the late Middle Ages, Spanish philosopher Dominicus Gundissalinus translated a treatise by the earlier Persian scholar Al-Farabi called *On the Sciences* into Latin, calling the study of the mechanics of nature *scientia naturalis*, or natural science. Gundissalinus also proposed his own classification of the natural sciences in his 1150 work *On the Division of Philosophy*. This was the first detailed classification of the sciences based on Greek and Arab philosophy to reach Western Europe. Gundissalinus defined natural science as "the science considering only things unabstracted and with motion," as opposed to mathematics and sciences that rely on mathematics. Following Al-Farabi, he then separated the sciences into eight parts, including physics, cosmology, meteorology, minerals science, and plant and animal science.

Later philosophers made their own classifications of the natural sciences. Robert Kilwardby wrote *On the Order of the Sciences* in the 13th century that classed medicine as a mechanical science, along with agriculture, hunting and theater while defining natural science as the science that deals with bodies in motion. Roger Bacon, an English friar and philosopher, wrote that natural science dealt with "a principle of motion and rest, as in the parts of the elements of fire, air, earth and water, and in all inanimate things made from them." These sciences also covered plants, animals and celestial bodies. Later in the 13th century, a Catholic priest and theologian Thomas Aquinas defined natural science as dealing with "mobile beings" and "things which depend on a matter not only for their existence but also for their definition." There was wide agreement among scholars in medieval times that natural science was about bodies in motion, although there was division about the inclusion of fields including medicine, music and perspective. Philosophers pondered questions including the existence of a vacuum, whether motion could produce heat, the colors of rainbows, the motion of the earth, whether elemental chemicals exist, and where in the atmosphere rain is formed.

In the centuries up through the end of the Middle Ages, natural science was often mingled with philosophies about magic and the occult. Natural philosophy appeared in a wide range of forms, from treatises to encyclopedias to commentaries on Aristotle. The interaction between natural philosophy and Christianity was complex during this period; some early theologians, including Tatian and Eusebius, considered natural philosophy an outcropping of pagan Greek science and were suspicious of it. Although some later Christian philosophers, including Aquinas, came to see natural science as a means of interpreting scripture, this suspicion persisted until the 12th and 13th centuries. The Condemnation of 1277, which forbade setting philosophy on a level equal with theology and the debate of religious constructs in a scientific context, showed the persistence with which Catholic leaders resisted the development of natural philosophy even from a theological perspective. Aquinas and Albertus Magnus, another Catholic theologian of the era, sought to distance theology from science in their works. "I don't see what one's interpretation of Aristotle has to do with the teaching of the faith," he wrote in 1271.

Newton and the scientific revolution (1600–1800)

By the 16th and 17th centuries, natural philosophy underwent an evolution beyond commentary on Aristotle as more early Greek philosophy was uncovered and translated. The invention of the printing press in the 15th century, the invention of the microscope and telescope, and the Protestant Reformation fundamentally altered the social context in which scientific inquiry evolved in the West. Christopher Columbus's discovery of a new world changed perceptions about the physical makeup of the world, while observations by Copernicus, Tyco Brahe and Galileo brought a more accurate picture of the solar system as heliocentric and proved many of Aristotle's theories about the heavenly bodies false. A number of 17th-century philosophers, including Thomas Hobbes, John Locke and Francis Bacon made a break from the past by rejecting Aristotle and his medieval followers outright, calling their approach to natural philosophy as superficial.

The titles of Galileo's work *Two New Sciences* and Johannes Kepler's *New Astronomy* underscored the atmosphere of change that took hold in the 17th century as Aristotle was dismissed in favor of novel methods of inquiry into the natural world. Bacon was instrumental in popularizing this change; he argued that people should use the arts and sciences to gain dominion over nature. To achieve this, he wrote that "human life [must] be endowed with new discoveries and powers." He defined natural philosophy as "the knowledge of Causes and secret motions of things; and enlarging the bounds of Human Empire, to the effecting of all things possible." Bacon proposed that scientific inquiry be supported by the state and fed by the collaborative research of scientists, a vision that was unprecedented in its scope, ambition, and form at the time. Natural philosophers came to view nature increasingly as a mechanism that could be taken apart and understood, much like a complex clock. Natural philosophers including Isaac Newton, Evangelista Torricelli and Francesco Redi conducted experiments focusing on the flow of water, measuring atmospheric pressure using a barometer and disproving spontaneous generation. Scientific societies and scientific journals emerged and were spread widely through the printing press, touching off the scientific revolution. Newton in 1687 published his *The Mathematical Principles of Natural Philosophy*, or *Principia Mathematica*, which set the groundwork for physical laws that remained current until the 19th century.

Some modern scholars, including Andrew Cunningham, Perry Williams, and Floris Cohen, argue that natural philosophy is not properly called a science, and that genuine scientific inquiry began only with the scientific revolution. According to Cohen, "the emancipation of science from an overarching entity called 'natural philosophy' is one defining characteristic of the Scientific Revolution." Other historians of science, including Edward Grant, contend that the scientific revolution that blossomed in the 17th, 18th and 19th centuries occurred when principles learned in the exact sciences of optics, mechanics, and astronomy began to be applied to questions raised by natural philosophy. Grant argues that Newton attempted to expose the mathematical basis of nature – the immutable rules it obeyed – and in doing so joined natural philosophy and mathematics for the first time, producing an early work of modern physics.

The scientific revolution, which began to take hold in the 17th century, represented a sharp break from Aristotelian modes of inquiry. One of its principal advances was the use of the scientific method to investigate nature. Data was collected and repeatable measurements made in experiments. Scientists then formed hypotheses to explain the results of these experiments. The hypothesis was then tested using the principle of falsifiability to prove or disprove its accuracy. The natural sciences continued to be called natural philosophy, but the adoption of the scientific method took science beyond the realm of philosophical conjecture and introduced a more structured way of examining nature.

Newton, an English mathematician and physicist was the seminal figure in the scientific revolution. Drawing on advances made in astronomy by Copernicus, Brahe, and Kepler, Newton derived the universal law of gravitation and laws of motion. These laws applied both on earth and in outer space, uniting two spheres of the physical world previously thought to function independently of each other, according to separate physical rules. Newton, for example, showed that the tides were caused by the gravitational pull of the moon. Another of Newton's advances was to make mathematics a powerful explanatory tool for natural phenomena. While natural philosophers had long used mathematics as a means of measurement and analysis, its principles were not used as a means of understanding cause and effect in nature until Newton.

In the 18th century and 19th century, scientists including Charles-Augustin de Coulomb, Alessandro Volta, and Michael Faraday built upon Newtonian mechanics by exploring electromagnetism, or the interplay of forces with positive and negative charges on electrically charged particles. Faraday proposed that forces in nature operated in "fields" that filled space. The idea of fields contrasted with the Newtonian construct of gravitation as simply "action at a distance", or the attraction of objects with nothing in the space between them to intervene. James Clerk Maxwell in the 19th century unified these discoveries in a coherent theory of electrodynamics. Using mathematical equations and experimentation, Maxwell discovered that space was filled with charged particles that could act upon themselves and each other and that they were a medium for the transmission of charged waves.

Significant advances in chemistry also took place during the scientific revolution. Antoine Lavoisier, a French chemist, refuted the phlogiston theory, which posited that things burned by releasing "phlogiston" into the air. Joseph Priestley had discovered oxygen in the 18th century, but Lavoisier discovered that combustion was the result of oxidation. He also constructed a table of 33 elements and invented modern chemical nomenclature. Formal biological science remained in its infancy in the 18th century, when the focus lay upon the classification and categorization of natural life. This growth in natural history was led by Carl Linnaeus, whose 1735 taxonomy of the natural world is still in use. Linnaeus in the 1750s introduced scientific names for all his species.

19th-century developments (1800–1900)

By the 19th century, the study of science had come into the purview of professionals and institutions. In so doing, it gradually acquired the more modern name of *natural science.* The term *scientist* was coined by William Whewell in an 1834 review of Mary Somerville's *On the Connexion of the Sciences*. But the word did not enter general use until nearly the end of the same century.

Modern natural science (1900–present)

According to a famous 1923 textbook, *Thermodynamics and the Free Energy of Chemical Substances*, by the American chemist Gilbert N. Lewis and the American physical chemist Merle Randall, the natural sciences contain three great branches:

Aside from the logical and mathematical sciences, there are three great branches of *natural science* which stand apart by reason of the variety of far reaching deductions drawn from a small number of primary postulates — they are mechanics, electrodynamics, and thermodynamics.

Today, natural sciences are more commonly divided into life sciences, such as botany and zoology; and physical sciences, which include physics, chemistry, astronomy, and Earth sciences.

Chapter 15

History of Biology

The **history of biology** traces the study of the living world from ancient to modern times. Although the concept of *biology* as a single coherent field arose in the 19th century, the biological sciences emerged from traditions of medicine and natural history reaching back to ayurveda, ancient Egyptian medicine and the works of Aristotle and Galen in the ancient Greco-Roman world. This ancient work was further developed in the Middle Ages by Muslim physicians and scholars such as Avicenna. During the European Renaissance and early modern period, biological thought was revolutionized in Europe by a renewed interest in empiricism and the discovery of many novel organisms. Prominent in this movement were Vesalius and Harvey, who used experimentation and careful observation in physiology, and naturalists such as Linnaeus and Buffon who began to classify the diversity of life and the fossil record, as well as the development and behavior of organisms. Antonie van Leeuwenhoek revealed by means of microscopy the previously unknown world of microorganisms, laying the groundwork for cell theory. The growing importance of natural theology, partly a response to the rise of mechanical philosophy, encouraged the growth of natural history (although it entrenched the argument from design).

Over the 18th and 19th centuries, biological sciences such as botany and zoology became increasingly professional scientific disciplines. Lavoisier and other physical scientists began to connect the animate and inanimate worlds through physics and chemistry. Explorer-naturalists such as Alexander von Humboldt investigated the interaction between organisms and their environment, and the ways this relationship depends on geography—laying the foundations for biogeography, ecology and ethology. Naturalists began to reject essentialism and consider the importance of extinction and the mutability of species. Cell theory provided a new perspective on the fundamental basis of life. These developments, as well as the results from embryology and paleontology, were synthesized in Charles Darwin's theory of evolution by natural selection. The end of the 19th century saw the fall of spontaneous generation and the rise of the germ theory of disease, though the mechanism of inheritance remained a mystery.

In the early 20th century, the rediscovery of Mendel's work led to the rapid development of genetics by Thomas Hunt Morgan and his students, and by the 1930s the combination of population genetics and natural selection in the "neo-Darwinian synthesis". New disciplines developed rapidly, especially after Watson and Crick proposed the structure of DNA. Following the establishment of the Central Dogma and the cracking of the genetic code, biology was largely split between *organismal biology*—the fields that deal with whole organisms and groups of organisms—and the fields related to *cellular and molecular biology*. By the late 20th century, new fields like genomics and proteomics were reversing this trend, with organismal biologists using molecular techniques, and molecular and cell biologists investigating the interplay between genes and the environment, as well as the genetics of natural populations of organisms.

Prehistoric times

The earliest humans must have had and passed on knowledge about plants and animals to increase their chances of survival. This may have included knowledge of human and animal anatomy and aspects of animal behavior (such as migration patterns). However, the first major turning point in biological knowledge came with the Neolithic Revolution about 10,000 years ago. Humans first domesticated plants for farming, then livestock animals to accompany the resulting sedentary societies.

Earliest roots

In around 3000 to 1200 BCE, the Ancient Egyptians and Mesopotamians made contributions to astronomy, mathematics, and medicine, which later entered and shaped Greek natural philosophy of classical antiquity, a period that profoundly influenced the development of what came to be known as biology.

Ancient Egypt

Over a dozen medical papyri have been preserved, most notably the Edwin Smith Papyrus (the oldest extant surgical handbook) and the Ebers Papyrus (a handbook of preparing and using materia medica for various diseases), both from around 1600 BCE.

Ancient Egypt is also known for developing embalming, which was used for mummification, in order to preserve human remains and forestall decomposition.

Mesopotamia

The Mesopotamians seem to have had little interest in the natural world as such, preferring to study how the gods had ordered the universe. Animal physiology was studied for divination, including especially the anatomy of the liver, seen as an important organ in haruspicy. Animal behavior too was studied for divinatory purposes. Most information about the training and domestication of animals was probably transmitted orally, but one text dealing with the training of horses has survived.

The ancient Mesopotamians had no distinction between "rational science" and magic. When a person became ill, doctors prescribed both magical formulas to be recited and medicinal treatments. The earliest medical prescriptions appear in Sumerian during the Third Dynasty of Ur (c. 2112 – c. 2004 BCE). 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 BCE). In East Semitic cultures, the main medicinal authority was an exorcist-healer known as an*āšipu*. The profession was passed down from father to son and was held in high regard. Of less frequent recourse was the *asu*, a healer who treated physical symptoms using remedies composed of 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.

Separate developments in China and India

Observations and theories regarding nature and human health, separate from Western traditions, had emerged independently in other civilizations such as those in China and the Indian subcontinent. In ancient China, earlier conceptions can be found dispersed across several different disciplines, including the work of herbologists, physicians, alchemists, and philosophers. The Taoist tradition of Chinese alchemy, for example, emphasized health (with the ultimate goal being the elixir of life). The system of classical Chinese medicine usually revolved around the theory of yin and yang, and the five phases. Taoist philosophers, such as Zhuangzi in the 4th century BCE, also expressed ideas related to evolution, such as denying the fixity of biological species and speculating that species had developed differing attributes in response to differing environments.

One of the oldest organised systems of medicine is known from ancient India in the form of Ayurveda, which originated around 1500 BCE from Atharvaveda (one of the four most ancient books of Indian knowledge, wisdom and culture).

The ancient Indian Ayurveda tradition independently developed the concept of three humours, resembling that of the four humours of ancient Greek medicine, though the Ayurvedic system included further complications, such as the body being composed of five elements and seven basic tissues. Ayurvedic writers also classified living things into four categories based on the method of birth (from the womb, eggs, heat & moisture, and seeds) and explained the conception of a fetus in detail. They also made considerable advances in the field of surgery, often without the use of human dissection or animal vivisection. One of the earliest Ayurvedic treatises was the *Sushruta Samhita*, attributed to Sushruta in the 6th century BCE. It was also an early materia medica, describing 700 medicinal plants, 64 preparations from mineral sources, and 57 preparations based on animal sources.

Classical antiquity

The pre-Socratic philosophers asked many questions about life but produced little systematic knowledge of specifically biological interest—though the attempts of the atomists to explain life in purely physical terms would recur periodically through the history of biology. However, the medical theories of Hippocrates and his followers, especially humorism, had a lasting impact.

The philosopher Aristotle was the most influential scholar of the living world from classical antiquity. Though his early work in natural philosophy was speculative, Aristotle's later biological writings were more empirical, focusing on biological causation and the diversity of life. He made countless observations of nature, especially the habits and attributes of plants and animals in the world around him, which he devoted considerable attention to categorizing. In all, Aristotle classified 540 animal species, and dissected at least 50. He believed that intellectual purposes, formal causes, guided all natural processes.

Aristotle, and nearly all Western scholars after him until the 18th century, believed that creatures were arranged in a graded scale of perfection rising from plants on up to humans: the *scala naturae* or Great Chain of Being. Aristotle's successor at the Lyceum, Theophrastus, wrote a series of books on botany—the *History of Plants*—which survived as the most important contribution of antiquity to botany, even into the Middle Ages. Many of Theophrastus' names survive into modern times, such as *carpos* for fruit, and *pericarpion* for seed vessel. Dioscorides wrote a pioneering and encyclopaedic pharmacopoeia, *De Materia Medica*, incorporating descriptions of some 600 plants and their uses in medicine. Pliny the Elder, in his *Natural History*, assembled a similarly encyclopaedic account of things in nature, including accounts of many plants and animals.

A few scholars in the Hellenistic period under the Ptolemies—particularly Herophilus of Chalcedon and Erasistratus of Chios—amended Aristotle's physiological work, even performing dissections and vivisections. Claudius Galen became the most important authority on medicine and anatomy. Though a few ancient atomists such as Lucretius challenged the teleological Aristotelian viewpoint that all aspects of life are the result of design or purpose, teleology (and after the rise of Christianity, natural theology) would remain central to biological thought essentially until the 18th and 19th centuries. Ernst W. Mayr argued that "Nothing of any real consequence happened in biology after Lucretius and Galen until the Renaissance." The ideas of the Greek traditions of natural history and medicine survived, but they were generally taken unquestioningly in medieval Europe.

Middle Ages

- The decline of the Roman Empire led to the disappearance or destruction of much knowledge, though physicians still incorporated many aspects of the Greek tradition into training and practice. In Byzantium and the Islamic world, many of the Greek works were translated into Arabic and many of the works of Aristotle were preserved.

During the High Middle Ages, a few European scholars such as Hildegard of Bingen, Albertus Magnus and Frederick II wrote on natural history. The rise of European universities, though important for the development of physics and philosophy, had little impact on biological scholarship.

Renaissance

The European Renaissance brought expanded interest in both empirical natural history and physiology. In 1543, Andreas Vesalius inaugurated the modern era of Western medicine with his seminal human anatomy treatise *De humani corporis fabrica*, which was based on dissection of corpses. Vesalius was the first in a series of anatomists who gradually replaced scholasticism with empiricism in physiology and medicine, relying on first-hand experience rather than authority and abstract reasoning. Via herbalism, medicine was also indirectly the source of renewed empiricism in the study of plants. Otto Brunfels, Hieronymus Bock and Leonhart Fuchs wrote extensively on wild plants, the beginning of a nature-based approach to the full range of plant life. Bestiaries—a genre that combines both the natural and figurative knowledge of animals—also became more sophisticated, especially with the work of William Turner, Pierre Belon, Guillaume Rondelet, Conrad Gessner, and Ulisse Aldrovandi.

Artists such as Albrecht Dürer and Leonardo da Vinci, often working with naturalists, were also interested in the bodies of animals and humans, studying physiology in detail and contributing to the growth of anatomical knowledge. The traditions of alchemy and natural magic, especially in the work of Paracelsus, also laid claim to knowledge of the living world. Alchemists subjected organic matter to chemical analysis and experimented liberally with both biological and mineral pharmacology. This was part of a larger transition in world views (the rise of the mechanical philosophy) that continued into the 17th century, as the traditional metaphor of *nature as organism* was replaced by the *nature as machine* metaphor.

Age of Enlightenment

Systematizing, naming and classifying dominated natural history throughout much of the 17th and 18th centuries. Carl Linnaeus published a basic taxonomy for the natural world in

1735 (variations of which have been in use ever since), and in the 1750s introduced scientific names for all his species. While Linnaeus conceived of species as unchanging parts of a designed hierarchy, the other great naturalist of the 18th century, Georges-Louis Leclerc, Comte de Buffon, treated species as artificial categories and living forms as malleable—even suggesting the possibility of common descent. Though he was opposed to evolution, Buffon is a key figure in the history of evolutionary thought; his work would influence the evolutionary theories of both Lamarck and Darwin.

The discovery and description of new species and the collection of specimens became a passion of scientific gentlemen and a lucrative enterprise for entrepreneurs; many naturalists traveled the globe in search of scientific knowledge and adventure.

Extending the work of Vesalius into experiments on still living bodies (of both humans and animals), William Harvey and other natural philosophers investigated the roles of blood, veins and arteries. Harvey's *De motu cordis* in 1628 was the beginning of the end for Galenic theory, and alongside Santorio Santorio's studies of metabolism, it served as an influential model of quantitative approaches to physiology.

In the early 17th century, the micro-world of biology was just beginning to open up. A few lensmakers and natural philosophers had been creating crude microscopes since the late 16th century, and Robert Hooke published the seminal *Micrographia* based on observations with his own compound microscope in 1665. But it was not until Antonie van Leeuwenhoek's dramatic improvements in lensmaking beginning in the 1670s—ultimately producing up to 200-fold magnification with a single lens—that scholars discovered spermatozoa, bacteria, infusoria and the sheer strangeness and diversity of microscopic life. Similar investigations by Jan Swammerdam led to new interest in entomology and built the basic techniques of microscopic dissection and staining.

As the microscopic world was expanding, the macroscopic world was shrinking. Botanists such as John Ray worked to incorporate the flood of newly discovered organisms shipped from across the globe into a coherent taxonomy, and a coherent theology (natural theology). Debate over another flood, the Noachian, catalyzed the development of paleontology; in 1669 Nicholas Steno published an essay on how the remains of living organisms could be trapped in layers of sediment and mineralized to produce fossils. Although Steno's ideas about fossilization were well known and much debated among natural philosophers, an organic origin for all fossils would not be accepted by all naturalists until the end of the 18th century due to philosophical and theological debate about issues such as the age of the earth and extinction.

19th century: the emergence of biological disciplines

- Up through the 19th century, the scope of biology was largely divided between medicine, which investigated questions of form and function (i.e., physiology), and natural history, which was concerned with the diversity of life and interactions among different forms of life and between life and non-life. By 1900, much of these domains overlapped, while natural history (and its counterpart natural philosophy) had largely given way to more specialized scientific disciplines—cytology, bacteriology, morphology, embryology, geography, and geology.

Use of the term *biology*

The term *biology* in its modern sense appears to have been introduced independently by Thomas Beddoes (in 1799), Karl Friedrich Burdach (in 1800), Gottfried Reinhold Treviranus (*Biologie oder Philosophie der lebenden Natur*, 1802) and Jean-Baptiste Lamarck (*Hydrogéologie*, 1802). The word itself appears in the title of Volume 3 of Michael Christoph Hanow's *Philosophiae naturalis sive physicae dogmaticae: Geologia, biologia, phytologia generalis et dendrologia*, published in 1766.

Before *biology,* there were several terms used for the study of animals and plants. *Natural history* referred to the descriptive aspects of biology, though it also included mineralogy and other non-biological fields; from the Middle Ages through the Renaissance, the unifying framework of natural history was the *scala naturae* or Great Chain of Being. *Natural philosophy* and *natural theology* encompassed the conceptual and metaphysical basis of plant and animal life, dealing with problems of why organisms exist and behave the way they do, though these subjects also included what is now geology, physics, chemistry, and astronomy. Physiology and (botanical) pharmacology were the province of medicine. *Botany*, *zoology*, and (in the case of fossils) *geology* replaced *natural history* and *natural philosophy* in the 18th and 19th centuries before *biology* was widely adopted. To this day, "botany" and "zoology" are widely used, although they have been joined by other sub-disciplines of biology.

Natural history and natural philosophy

Widespread travel by naturalists in the early-to-mid-19th century resulted in a wealth of new information about the diversity and distribution of living organisms. Of particular importance was the work of Alexander von Humboldt, which analyzed the relationship between organisms and their environment (i.e., the domain of natural history) using the quantitative approaches of natural philosophy (i.e., physics and chemistry). Humboldt's work laid the foundations of biogeography and inspired several generations of scientists.

Geology and paleontology

The emerging discipline of geology also brought natural history and natural philosophy closer together; the establishment of the stratigraphic column linked the spatial distribution of organisms to their temporal distribution, a key precursor to concepts of evolution. Georges Cuvier and others made great strides in comparative anatomy and paleontology in the late 1790s and early 19th century. In a series of lectures and papers that made detailed comparisons between living mammals and fossil remains Cuvier was able to establish that the fossils were remains of species that had become extinct—rather than being remains of species still alive elsewhere in the world, as had been widely believed. Fossils discovered and described by Gideon Mantell, William Buckland, Mary Anning, and Richard Owen among others helped establish that there had been an 'age of reptiles' that had preceded even the prehistoric mammals. These discoveries captured the public imagination and focused attention on the history of life on earth. Most of these geologists held to catastrophism, but Charles Lyell's influential *Principles of Geology* (1830) popularised Hutton's uniformitarianism, a theory that explained the geological past and present on equal terms.

Evolution and biogeography

The most significant evolutionary theory before Darwin's was that of Jean-Baptiste Lamarck; based on the inheritance of acquired characteristics (an inheritance mechanism that was widely accepted until the 20th century), it described a chain of development stretching from the lowliest microbe to humans. The British naturalist Charles Darwin, combining the biogeographical approach of Humboldt, the uniformitarian geology of Lyell, Thomas Malthus's writings on population growth, and his own morphological expertise, created a more successful evolutionary theory based on natural selection; similar evidence led Alfred Russel Wallace to independently reach the same conclusions.

The 1859 publication of Darwin's theory in *On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life* is often considered the central event in the history of modern biology. Darwin's established credibility as a naturalist, the sober tone of the work, and most of all the sheer strength and volume of evidence presented, allowed *Origin* to succeed where previous evolutionary works such as the anonymous *Vestiges of Creation* had failed. Most scientists were convinced of evolution and common descent by the end of the 19th century. However, natural selection would not be accepted as the primary mechanism of evolution until well into the 20th century, as most contemporary theories of heredity seemed incompatible with the inheritance of random variation.

Wallace, following on earlier work by de Candolle, Humboldt and Darwin, made major contributions to zoogeography. Because of his interest in the transmutation hypothesis, he paid particular attention to the geographical distribution of closely allied species during his field work first in South America and then in the Malay archipelago. While in the archipelago he identified the Wallace line, which runs through the Spice Islands dividing the fauna of the archipelago between an Asian zone and a New Guinea/Australian zone. His key question, as to why the fauna of islands with such similar climates should be so different, could only be answered by considering their origin. In 1876 he wrote *The Geographical Distribution of Animals*, which was the standard reference work for over half a century, and a sequel, *Island Life*, in 1880 that focused on island biogeography. He extended the six-zone system developed by Philip Sclater for describing the geographical distribution of birds to animals of all kinds. His method of tabulating data on animal groups in geographic zones highlighted the discontinuities; and his appreciation of evolution allowed him to propose rational explanations, which had not been done before.

The scientific study of heredity grew rapidly in the wake of Darwin's *Origin of Species* with the work of Francis Galton and the biometricians. The origin of genetics is usually traced to the 1866 work of the monk Gregor Mendel, who would later be credited with the laws of inheritance. However, his work was not recognized as significant until 35 years afterward. In the meantime, a variety of theories of inheritance (based on pangenesis, orthogenesis, or other mechanisms) were debated and investigated vigorously. Embryology and ecology also became central biological fields, especially as linked to evolution and popularized in the work of Ernst Haeckel. Most of the 19th century work on heredity, however, was not in the realm of natural history, but that of experimental physiology.

Physiology

Over the course of the 19th century, the scope of physiology expanded greatly, from a primarily medically oriented field to a wide-ranging investigation of the physical and chemical processes of life—including plants, animals, and even microorganisms in addition to man. *Living things as machines* became a dominant metaphor in biological (and social) thinking.

Cell theory, embryology and germ theory

Advances in microscopy also had a profound impact on biological thinking. In the early 19th century, a number of biologists pointed to the central importance of the cell. In 1838 and 1839, Schleiden and Schwann began promoting the ideas that (1) the basic unit of organisms is the cell and (2) that individual cells have all the characteristics of life, though they opposed the idea that (3) all cells come from the division of other cells. Thanks to the work of Robert Remak and Rudolf Virchow, however, by the 1860s most biologists accepted all three tenets of what came to be known as cell theory.

Cell theory led biologists to re-envision individual organisms as interdependent assemblages of individual cells. Scientists in the rising field of cytology, armed with increasingly powerful microscopes and new staining methods, soon found that even single cells were far more complex than the homogeneous fluid-filled chambers described by earlier microscopists. Robert Brown had described the nucleus in 1831, and by the end of the 19th century cytologists identified many of the key cell components: chromosomes, centrosomes mitochondria, chloroplasts, and other structures made visible through staining. Between 1874 and 1884 Walther Flemming described the discrete stages of mitosis, showing that they were not artifacts of staining but occurred in living cells, and moreover, that chromosomes doubled in number just before the cell divided and a daughter cell was produced. Much of the research on cell reproduction came together in August Weismann's theory of heredity: he identified the nucleus (in particular chromosomes) as the hereditary material, proposed the distinction between somatic cells and germ cells (arguing that chromosome number must be halved for germ cells, a precursor to the concept of meiosis), and adopted Hugo de Vries's theory of pangenes. Weismannism was extremely influential, especially in the new field of experimental embryology.

By the mid-1850s the miasma theory of disease was largely superseded by the germ theory of disease, creating extensive interest in microorganisms and their interactions with other forms of life. By the 1880s, bacteriology was becoming a coherent discipline, especially through the work of Robert Koch, who introduced methods for growing pure cultures on agar gels containing specific nutrients in Petri dishes. The long-held idea that living organisms could easily originate from nonliving matter (spontaneous generation) was attacked in a series of experiments carried out by Louis Pasteur, while debates over vitalism vs. mechanism (a perennial issue since the time of Aristotle and the Greek atomists) continued apace.

Rise of organic chemistry and experimental physiology

In chemistry, one central issue was the distinction between organic and inorganic substances, especially in the context of organic transformations such as fermentation and putrefaction. Since Aristotle these had been considered essentially biological (*vital*) processes. However, Friedrich Wöhler, Justus Liebig and other pioneers of the rising field of organic chemistry—building on the work of Lavoisier—showed that the organic world could often be analyzed by physical and chemical methods. In 1828 Wöhler showed that the organic substance urea could be created by chemical means that do not involve life, providing a powerful challenge to vitalism. Cell extracts ("ferments") that could effect chemical transformations were discovered, beginning with diastase in 1833. By the end of the 19th century the concept of enzymes was well established, though equations of chemical kinetics would not be applied to enzymatic reactions until the early 20th century.

Physiologists such as Claude Bernard explored (through vivisection and other experimental methods) the chemical and physical functions of living bodies to an unprecedented degree, laying the groundwork for endocrinology (a field that developed quickly after the discovery of the first hormone, secretin, in 1902), biomechanics, and the study of nutrition and digestion. The importance and diversity of experimental physiology methods, within both medicine and biology, grew dramatically over the second half of the 19th century. The control and manipulation of life processes became a central concern, and experiment was placed at the center of biological education.

Twentieth century biological sciences

At the beginning of the 20th century, biological research was largely a professional endeavour. Most work was still done in the natural history mode, which emphasized morphological and phylogenetic analysis over experiment-based causal explanations. However, anti-vitalist experimental physiologists and embryologists, especially in Europe, were increasingly influential. The tremendous success of experimental approaches to development, heredity, and metabolism in the 1900s and 1910s demonstrated the power of experimentation in biology. In the following decades, experimental work replaced natural history as the dominant mode of research.

Ecology and environmental science

In the early 20th century, naturalists were faced with increasing pressure to add rigor and preferably experimentation to their methods, as the newly prominent laboratory-based biological disciplines had done. Ecology had emerged as a combination of biogeography with the biogeochemical cycle concept pioneered by chemists; field biologists developed quantitative methods such as the quadrat and adapted laboratory instruments and cameras for the field to further set their work apart from traditional natural history. Zoologists and botanists did what they could to mitigate the unpredictability of the living world, performing laboratory experiments and studying semi-controlled natural environments such as gardens; new institutions like the Carnegie Station for Experimental Evolution and the Marine Biological Laboratory provided more controlled environments for studying organisms through their entire life cycles.

The ecological succession concept, pioneered in the 1900s and 1910s by Henry Chandler Cowles and Frederic Clements, was important in early plant ecology. Alfred Lotka's predator-prey equations, G. Evelyn Hutchinson's studies of the biogeography and biogeochemical structure of lakes and rivers (limnology) and Charles Elton's studies of animal food chains were pioneers among the succession of quantitative methods that colonized the developing ecological specialties. Ecology became an independent discipline in the 1940s and 1950s after Eugene P. Odum synthesized many of the concepts of ecosystem ecology, placing relationships between groups of organisms (especially material and energy relationships) at the center of the field.

In the 1960s, as evolutionary theorists explored the possibility of multiple units of selection, ecologists turned to evolutionary approaches. In population ecology, debate over group selection was brief but vigorous; by 1970, most biologists agreed that natural selection was rarely effective above the level of individual organisms. The evolution of ecosystems, however, became a lasting research focus. Ecology expanded rapidly with the rise of the environmental movement; the International Biological Program attempted to apply the methods of big science (which had been so successful in the physical sciences) to ecosystem ecology and pressing environmental issues, while smaller-scale independent efforts such as island biogeography and the Hubbard Brook Experimental Forest helped redefine the scope of an increasingly diverse discipline.

Classical genetics, the modern synthesis, and evolutionary theory

1900 marked the so-called *rediscovery of Mendel*: Hugo de Vries, Carl Correns, and Erich von Tschermak independently arrived at Mendel's laws (which were not actually present in Mendel's work). Soon after, cytologists (cell biologists) proposed that chromosomes were the hereditary material. Between 1910 and 1915, Thomas Hunt Morgan and the "Drosophilists" in his fly lab forged these two ideas—both controversial—into the "Mendelian-chromosome theory" of heredity. They quantified the phenomenon of genetic linkage and postulated that genes reside on chromosomes like beads on string; they hypothesized crossing over to explain linkage and constructed genetic maps of the fruit fly *Drosophila melanogaster*, which became a widely used model organism.

Hugo de Vries tried to link the new genetics with evolution; building on his work with heredity and hybridization, he proposed a theory of mutationism, which was widely accepted in the early 20th century. Lamarckism, or the theory of inheritance of acquired characteristics also had many adherents. Darwinism was seen as incompatible with the continuously variable traits studied by biometricians, which seemed only partially heritable. In the 1920s and 1930s— following the acceptance of the Mendelian-chromosome theory— the emergence of the discipline of population genetics, with the work of R.A. Fisher, J.B.S. Haldane and Sewall Wright, unified the idea of evolution by natural selection with Mendelian genetics, producing the modern synthesis. The inheritance of acquired characters was rejected, while mutationism gave way as genetic theories matured.

In the second half of the century the ideas of population genetics began to be applied in the new discipline of the genetics of behavior, sociobiology, and, especially in humans, evolutionary psychology. In the 1960s W.D. Hamilton and others developed game theory approaches to explain altruism from an evolutionary perspective through kin selection. The possible origin of higher organisms through endosymbiosis, and contrasting approaches to molecular evolution in the gene-centered view (which held selection as the predominant cause of evolution) and the neutral theory (which made genetic drift a key factor) spawned perennial debates over the proper balance of adaptationism and contingency in evolutionary theory.

In the 1970s Stephen Jay Gould and Niles Eldredge proposed the theory of punctuated equilibrium which holds that stasis is the most prominent feature of the fossil record, and that most evolutionary changes occur rapidly over relatively short periods of time. In 1980 Luis Alvarez and Walter Alvarez proposed the hypothesis that an impact event was responsible for the Cretaceous–Paleogene extinction event. Also in the early 1980s, statistical analysis of the fossil record of marine organisms published by Jack Sepkoski and David M. Raup led to a better appreciation of the importance of mass extinction events to the history of life on earth.

Biochemistry, microbiology, and molecular biology

By the end of the 19th century all of the major pathways of drug metabolism had been discovered, along with the outlines of protein and fatty acid metabolism and urea synthesis. In the early decades of the 20th century, the minor components of foods in human nutrition, the vitamins, began to be isolated and synthesized. Improved laboratory techniques such as chromatography and electrophoresis led to rapid advances in physiological chemistry, which—as *biochemistry*—began to achieve independence from its medical origins. In the 1920s and 1930s, biochemists—led by Hans Krebs and Carl and Gerty Cori—began to work out many of the central metabolic pathways of life: the citric acid cycle, glycogenesis and glycolysis, and the synthesis of steroids and porphyrins. Between the 1930s and 1950s, Fritz Lipmann and others established the role of ATP as the universal carrier of energy in the cell, and mitochondria as the powerhouse of the cell. Such traditionally biochemical work continued to be very actively pursued throughout the 20th century and into the 21st.

Origins of molecular biology

Following the rise of classical genetics, many biologists—including a new wave of physical scientists in biology—pursued the question of the gene and its physical nature. Warren Weaver—head of the science division of the Rockefeller Foundation—issued grants to promote research that applied the methods of physics and chemistry to basic biological problems, coining the term *molecular biology* for this approach in 1938; many of the significant biological breakthroughs of the 1930s and 1940s were funded by the Rockefeller Foundation.

Like biochemistry, the overlapping disciplines of bacteriology and virology (later combined as *microbiology*), situated between science and medicine, developed rapidly in the early 20th century. Félix d'Herelle's isolation of bacteriophage during World War I initiated a long line of research focused on phage viruses and the bacteria they infect.

The development of standard, genetically uniform organisms that could produce repeatable experimental results was essential for the development of molecular genetics. After early work with *Drosophila* and maize, the adoption of simpler model systems like the bread mold *Neurospora crassa* made it possible to connect genetics to biochemistry, most importantly with Beadle and Tatum's one gene-one enzyme hypothesis in 1941. Genetics experiments on even simpler systems like tobacco mosaic virus and bacteriophage, aided by the new technologies of electron microscopy and ultracentrifugation, forced scientists to re-evaluate the literal meaning of *life*; virus heredity and reproducing nucleoprotein cell structures outside the nucleus ("plasmagenes") complicated the accepted Mendelian-chromosome theory.

Oswald Avery showed in 1943 that DNA was likely the genetic material of the chromosome, not its protein; the issue was settled decisively with the 1952 Hershey–Chase experiment—one of many contributions from the so-called phage group centered around physicist-turned-biologist Max Delbrück. In 1953 James Watson and Francis Crick, 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", Watson and Crick noted coyly, "It has not escaped our notice that the specific pairing we have postulated immediately suggests a possible copying mechanism for the genetic material." After the 1958 Meselson–Stahl experiment confirmed the semiconservative replication of DNA, it was clear to most biologists that nucleic acid sequence must somehow determine amino acid sequence in proteins; physicist George Gamow proposed that a fixed genetic code connected proteins and DNA. Between 1953 and 1961, there were few known biological sequences—either DNA or protein—but an abundance of proposed code systems, a situation made even more complicated by expanding knowledge of the intermediate role of RNA. To actually decipher the code, it took an extensive series of experiments in biochemistry and bacterial genetics, between 1961 and 1966—most importantly the work of Nirenberg and Khorana.

Expansion of molecular biology

In addition to the Division of Biology at Caltech, the Laboratory of Molecular Biology (and its precursors) at Cambridge, and a handful of other institutions, the Pasteur Institute became a major center for molecular biology research in the late 1950s. Scientists at Cambridge, led by Max Perutz and John Kendrew, focused on the rapidly developing field of structural biology, combining X-ray crystallography with Molecular modelling and the new computational possibilities of digital computing (benefiting both directly and indirectly from the military funding of science). A number of biochemists led by Frederick Sanger later joined the Cambridge lab, bringing together the study of macromolecular structure and function. At the Pasteur Institute, François Jacob and Jacques Monod followed the 1959 PaJaMo experiment with a series of publications regarding the *lac* operon that established the concept of gene regulation and identified what came to be known as messenger RNA. By the mid-1960s, the intellectual core of molecular biology—a model for the molecular basis of metabolism and reproduction— was largely complete.

The late 1950s to the early 1970s was a period of intense research and institutional expansion for molecular biology, which had only recently become a somewhat coherent discipline. In what organismic biologist E. O. Wilson called "The Molecular Wars", the methods and practitioners of molecular biology spread rapidly, often coming to dominate departments and even entire disciplines. Molecularization was particularly important in genetics, immunology, embryology, and neurobiology, while the idea that life is controlled by a "genetic program"—a metaphor Jacob and Monod introduced from the emerging fields of cybernetics and computer science—became an influential perspective throughout biology. Immunology in particular became linked with molecular biology, with innovation flowing both ways: the clonal selection theory developed by Niels Jerne and Frank Macfarlane Burnet in the mid-1950s helped shed light on the general mechanisms of protein synthesis.

Resistance to the growing influence of molecular biology was especially evident in evolutionary biology. Protein sequencing had great potential for the quantitative study of evolution (through the molecular clock hypothesis), but leading evolutionary biologists questioned the relevance of molecular biology for answering the big questions of evolutionary causation. Departments and disciplines fractured as organismic biologists asserted their importance and independence: Theodosius Dobzhansky made the famous statement that "nothing in biology makes sense except in the light of evolution" as a response to the molecular challenge. The issue became even more critical after 1968; Motoo Kimura's neutral theory of molecular evolution suggested that natural selection was not the ubiquitous cause of evolution, at least at the molecular level, and that molecular evolution might be a fundamentally different process from morphological evolution. (Resolving this "molecular/morphological paradox" has been a central focus of molecular evolution research since the 1960s.)

Biotechnology, genetic engineering, and genomics

Biotechnology in the general sense has been an important part of biology since the late 19th century. With the industrialization of brewing and agriculture, chemists and biologists became aware of the great potential of human-controlled biological processes. In particular, fermentation proved a great boon to chemical industries. By the early 1970s, a wide range of biotechnologies were being developed, from drugs like penicillin and steroids to foods like *Chlorella* and single-cell protein to gasohol—as well as a wide range of hybrid high-yield crops and agricultural technologies, the basis for the Green Revolution.

Recombinant DNA

Biotechnology in the modern sense of genetic engineering began in the 1970s, with the invention of recombinant DNA techniques. Restriction enzymes were discovered and characterized in the late 1960s, following on the heels of the isolation, then duplication, then synthesis of viral genes. Beginning with the lab of Paul Berg in 1972 (aided by *EcoRI* from Herbert Boyer's lab, building on work with ligase by Arthur Kornberg's lab), molecular biologists put these pieces together to produce the first transgenic organisms. Soon after, others began using plasmid vectors and adding genes for antibiotic resistance, greatly increasing the reach of the recombinant techniques.

Wary of the potential dangers (particularly the possibility of a prolific bacteria with a viral cancer-causing gene), the scientific community as well as a wide range of scientific outsiders reacted to these developments with both enthusiasm and fearful restraint. Prominent molecular biologists led by Berg suggested a temporary moratorium on recombinant DNA research until the dangers could be assessed and policies could be created. This moratorium was largely respected, until the participants in the 1975 Asilomar Conference on Recombinant DNA created policy recommendations and concluded that the technology could be used safely.

Following Asilomar, new genetic engineering techniques and applications developed rapidly. DNA sequencing methods improved greatly (pioneered by Frederick Sanger and Walter Gilbert), as did oligonucleotide synthesis and transfection techniques. Researchers learned to control the expression of transgenes, and were soon racing—in both academic and industrial contexts—to create organisms capable of expressing human genes for the production of human hormones. However, this was a more daunting task than molecular biologists had expected; developments between 1977 and 1980 showed that, due to the phenomena of split genes and splicing, higher organisms had a much more complex system of gene expression than the bacteria models of earlier studies. The first such race, for synthesizing human insulin, was won by Genentech. This marked the beginning of the biotech boom (and with it, the era of gene patents), with an unprecedented level of overlap between biology, industry, and law.

Molecular systematics and genomics

By the 1980s, protein sequencing had already transformed methods of scientific classification of organisms (especially cladistics) but biologists soon began to use RNA and DNA sequences as characters; this expanded the significance of molecular evolution within evolutionary biology, as the results of molecular systematics could be compared with traditional evolutionary trees based on morphology. Following the pioneering ideas of Lynn Margulis on endosymbiotic theory, which holds that some of the organelles of eukaryotic cells originated from free living prokaryotic organisms through symbiotic relationships, even the overall division of the tree of life was revised. Into the 1990s, the five domains (Plants, Animals, Fungi, Protists, and Monerans) became three (the Archaea, the Bacteria, and the Eukarya) based on Carl Woese's pioneering molecular systematics work with 16S rRNA sequencing.

The development and popularization of the polymerase chain reaction (PCR) in mid-1980s (by Kary Mullis and others at Cetus Corp.) marked another watershed in the history of modern biotechnology, greatly increasing the ease and speed of genetic analysis. Coupled with the use of expressed sequence tags, PCR led to the discovery of many more genes than could be found through traditional biochemical or genetic methods and opened the possibility of sequencing entire genomes.

The unity of much of the morphogenesis of organisms from fertilized egg to adult began to be unraveled after the discovery of the homeobox genes, first in fruit flies, then in other insects and animals, including humans. These developments led to advances in the field of evolutionary developmental biology towards understanding how the various body plans of the animal phyla have evolved and how they are related to one another.

The Human Genome Project—the largest, most costly single biological study ever undertaken—began in 1988 under the leadership of James D. Watson, after preliminary work with genetically simpler model organisms such as *E. coli*, *S. cerevisiae* and *C. elegans*. Shotgun sequencing and gene discovery methods pioneered by Craig Venter—and fueled by the financial promise of gene patents with Celera Genomics—led to a public–private sequencing competition that ended in compromise with the first draft of the human DNA sequence announced in 2000.

Twenty-first century biological sciences

At the beginning of the 21st century, biological sciences converged with previously differentiated new and classic disciplines like Physics into research fields like Biophysics. Advances were made in analytical chemistry and physics instrumentation including improved sensors, optics, tracers, instrumentation, signal processing, networks, robots, satellites, and compute power for data collection, storage, analysis, modeling, visualization, and simulations. These technology advances allowed theoretical and experimental research including internet publication of molecular biochemistry, biological systems, and ecosystems science. This enabled worldwide access to better measurements, theoretical models, complex simulations, theory predictive model experimentation, analysis, worldwide internet observational data reporting, open peer-review, collaboration, and internet publication. New fields of biological sciences research emerged including Bioinformatics, Neuroscience, Theoretical biology, Computational genomics, Astrobiology and Synthetic Biology.

Chapter 16

History of Biochemistry

The **history of biochemistry** can be said to have started with the ancient Greeks who were interested in the composition and processes of life, although biochemistry as a specific scientific discipline has its beginning around the early 19th century. Some argued that the beginning of biochemistry may have been the discovery of the first enzyme, diastase (today called amylase), in 1833 by Anselme Payen, while others considered Eduard Buchner's first demonstration of a complex biochemical process alcoholic fermentation in cell-free extracts to be the birth of biochemistry. Some might also point to the influential work of Justus von Liebig from 1842, *Animal chemistry, or, Organic chemistry in its applications to physiology and pathology*, which presented a chemical theory of metabolism, or even earlier to the 18th century studies on fermentation and respiration by Antoine Lavoisier.

The term “biochemistry” itself is derived from the combining form *bio-*, meaning "life", and *chemistry*. The word is first recorded in English in 1848, while in 1877, Felix Hoppe-Seyler used the term (*Biochemie* in German) in the foreword to the first issue of *Zeitschrift für Physiologische Chemie* (Journal of Physiological Chemistry) as a synonym for physiological chemistry and argued for the setting up of institutes dedicate to its studies. Nevertheless, several sources cite German chemist Carl Neuberg as having coined the term for the new discipline in 1903, and some credit it to Franz Hofmeister.

The subject of study in biochemistry is the chemical processes in living organisms, and its history involves the discovery and understanding of the complex components of life and the elucidation of pathways of biochemical processes. Much of biochemistry deals with the structures and functions of cellular components such as proteins, carbohydrates, lipids, nucleic acids and other biomolecules; their metabolic pathways and flow of chemical energy through metabolism; how biological molecules give rise to the processes that occur within living cells; it also focuses on the biochemical processes involved in the control of information flow through biochemical signalling, and how they relate to the functioning of whole organisms. Over the last 40 years the field has had success in explaining living processes such that now almost all areas of the life sciences from botany to medicine are engaged in biochemical research.

Among the vast number of different biomolecules, many are complex and large molecules (called polymers), which are composed of similar repeating subunits (called monomers). Each class of polymeric biomolecule has a different set of subunit types. For example, a protein is a polymer whose subunits are selected from a set of twenty or more amino acids, carbohydrates are formed from sugars known as monosaccharides, oligosaccharides, and polysaccharides, lipids are formed from fatty acids and glycerols, and nucleic acids are formed from nucleotides. Biochemistry studies the chemical properties of important biological molecules, like proteins, and in particular the chemistry of enzyme-catalyzed reactions. The biochemistry of cell metabolism and the endocrine system has been extensively described. Other areas of biochemistry include the genetic code (DNA, RNA), protein synthesis, cell membrane transport, and signal transduction.

Proto-biochemistry

In a sense, the study of biochemistry can be considered to have started in ancient times, for example when biology first began to interest society—as the ancient Chinese developed a system of medicine based on yin and yang, and also the five phases, which both resulted from alchemical and biological interests. Its beginning in the ancient Indian culture was linked to an interest in medicine, as they developed the concept of three humors that were similar to the Greek's four humours (see humorism). They also delved into the interest of bodies being composed of tissues. The ancient Greeks conception of "biochemistry" was linked with their ideas on matter and disease, where good health was thought to come from a balance of the four elements and four humors in the human body. As in the majority of early sciences, the Islamic world contributed significantly to early biological advancements as well as alchemical advancements; especially with the introduction of clinical trials and clinical pharmacology presented in Avicenna's *The Canon of Medicine*. On the side of chemistry, early advancements were heavily attributed to exploration of alchemical interests but also included: metallurgy, the scientific method, and early theories of atomism. In more recent times, the study of chemistry was marked by milestones such as the development of Mendeleev's periodic table, Dalton's atomic model, and the conservation of mass theory. This last mention has the most importance of the three due to the fact that this law intertwines chemistry with thermodynamics in an intercalated manner.

Enzymes

As early as the late 18th century and early 19th century, the digestion of meat by stomach secretions and the conversion of starch to sugars by plant extracts and saliva were known. However, the mechanism by which this occurred had not been identified.

In the 19th century, when studying the fermentation of sugar to alcohol by yeast, Louis Pasteur concluded that this fermentation was catalyzed by a vital force contained within the yeast cells called *ferments*, which he thought functioned only within living organisms. He wrote that "alcoholic fermentation is an act correlated with the life and organization of the yeast cells, not with the death or putrefaction of the cells."

In 1833 Anselme Payen discovered the first enzyme, diastase, and in 1878 German physiologist Wilhelm Kühne (1837–1900) coined the term *enzyme*, which comes from Greek *ενζυμον* "in leaven", to describe this process. The word *enzyme* was used later to refer to nonliving substances such as pepsin, and the word *ferment* used to refer to chemical activity produced by living organisms.

In 1897 Eduard Buchner began to study the ability of yeast extracts to ferment sugar despite the absence of living yeast cells. In a series of experiments at the University of Berlin, he found that the sugar was fermented even when there were no living yeast cells in the mixture. He named the enzyme that brought about the fermentation of sucrose "zymase". In 1907 he received the Nobel Prize in Chemistry "for his biochemical research and his discovery of cell-free fermentation". Following Buchner's example; enzymes are usually named according to the reaction they carry out. Typically the suffix *-ase* is added to the name of the substrate (*e.g.*, lactase is the enzyme that cleaves lactose) or the type of reaction (*e.g.*, DNA polymerase forms DNA polymers).

Having shown that enzymes could function outside a living cell, the next step was to determine their biochemical nature. Many early workers noted that enzymatic activity was associated with proteins, but several scientists (such as Nobel laureate Richard Willstätter) argued that proteins were merely carriers for the true enzymes and that proteins *per se* were incapable of catalysis. However, in 1926, James B. Sumner showed that the enzyme urease was a pure protein and crystallized it; Sumner did likewise for the enzyme catalase in 1937. The conclusion that pure proteins can be enzymes was definitively proved by Northrop and Stanley, who worked on the digestive enzymes pepsin (1930), trypsin and chymotrypsin. These three scientists were awarded the 1946 Nobel Prize in Chemistry.

This discovery, that enzymes could be crystallized, meant that scientists eventually could solve their structures by x-ray crystallography. This was first done for lysozyme, an enzyme found in tears, saliva and egg whites that digests the coating of some bacteria; the structure was solved by a group led by David Chilton Phillips and published in 1965. This highresolution structure of lysozyme marked the beginning of the field of structural biology and the effort to understand how enzymes work at an atomic level of detail.

Metabolism

Early metabolic interest

The term *metabolism* is derived from the Greek Μεταβολισμός– Metabolismos for "change", or "overthrow". The history of the scientific study of metabolism spans 800 years. The earliest of all metabolic studies began during the early thirteenth century (1213-1288) by a Muslim scholar from Damascus named Ibn al-Nafis. al-Nafis stated in his most well-known work *Theologus Autodidactus* that "that body and all its parts are in a continuous state of dissolution and nourishment, so they are inevitably undergoing permanent change." Although al-Nafis was the first documented physician to have an interest in biochemical concepts, the first controlled experiments in human metabolism were published by Santorio Santorio in 1614 in his book *Ars de statica medecina*. This book describes how he weighed himself before and after eating, sleeping, working, sex, fasting, drinking, and excreting. He found that most of the food he took in was lost through what he called "insensible perspiration".

Metabolism: 20th century - present

One of the most prolific of these modern biochemists was Hans Krebs who made huge contributions to the study of metabolism. Krebs was a student of extremely important Otto Warburg, and wrote a biography of Warburg by that title in which he presents Warburg as being educated to do for biological chemistry what Fischer did for organic chemistry. Which he did. Krebs discovered the urea cycle and later, working with Hans Kornberg, the citric acid cycle and the glyoxylate cycle. These discoveries led to Krebs being awarded the Nobel Prize in physiology in 1953, which was shared with the German biochemist Fritz Albert Lipmann who also codiscovered the essential cofactor coenzyme A.

Glucose absorption

In 1960, the biochemist Robert K. Crane revealed his discovery of the sodium-glucose cotransport as the mechanism for intestinal glucose absorption. This was the very first proposal of a coupling between the fluxes of an ion and a substrate that has been seen as sparking a revolution in biology. This discovery, however, would not have been possible if it were not for the discovery of the molecule glucose's structure and chemical makeup. These discoveries are largely attributed to the German chemist Emil Fischer who received the Nobel Prize in chemistry nearly 60 years earlier.

Glycolysis

Since metabolism focuses on the breaking down (catabolic processes) of molecules and the building of larger molecules from these particles (anabolic processes), the use of glucose and its involvement in the formation of adenosine triphosphate (ATP) is fundamental to this understanding. The most frequent type of glycolysis found in the body is the type that follows the Embden-Meyerhof-Parnas (EMP) Pathway, which was discovered by Gustav Embden, Otto Meyerhof, and Jakob Karol Parnas. These three men discovered that glycolysis is a strongly determinant process for the efficiency and production of the human body. The significance of the pathway shown in the adjacent image is that by identifying the individual steps in this process doctors and researchers are able to pinpoint sites of metabolic malfunctions such as pyruvate kinase deficiency that can lead to severe anemia. This is most important because cells, and therefore organisms, are not capable of surviving without proper functioning metabolic pathways.

Instrumental advancements (20th century)

Since then, biochemistry has advanced, especially since the mid-20th century, with the development of new techniques such as chromatography, X-ray diffraction, NMR spectroscopy, radioisotopic labelling, electron microscopy and molecular dynamics simulations. These techniques allowed for the discovery and detailed analysis of many molecules and metabolic pathways of the cell, such as glycolysis and the Krebs cycle (citric acid cycle). The example of an NMR instrument shows that some of these instruments, such as the HWB-NMR, can be very large in size and can cost anywhere from a few thousand dollars to millions of dollars ($16 million for the one shown here).

Polymerase chain reaction

- Polymerase chain reaction (PCR) is the primary gene amplification technique that has revolutionized modern biochemistry. Polymerase chain reaction was developed by Kary Mullis in 1983. There are four steps to a proper polymerase chain reaction: 1) denaturation 2) extension 3) insertion (of gene to be expressed) and finally 4) amplification of the inserted gene. These steps with simple illustrative examples of this process can be seen in the image below and to the right of this section. This technique allows for the copy of a single gene to be amplified into hundreds or even millions of copies and has become a cornerstone in the protocol for any biochemist that wishes to work with bacteria and gene expression. PCR is not only used for gene expression research but is also capable of aiding laboratories in diagnosing certain diseases such a lymphomas, some types of leukemia, and other malignant diseases that can sometimes puzzle doctors. Without polymerase chain reaction development, there are many advancements in the field of bacterial study and protein expression study that would not have come to fruition. The development of the theory and process of polymerase chain reaction is essential but the invention of the thermal cycler is equally as important because the process would not be possible without this instrument. This is yet another testament to the fact that the advancement of technology is just as crucial to sciences such as biochemistry as is the painstaking research that leads to the development of theoretical concepts.

Chapter 17

History of Science and Technology

The **history of science and technology** (**HST**) is a field of history that examines how the understanding of the natural world (science) and the ability to manipulate it (technology) have changed over the millennia and centuries. This academic discipline also studies the cultural, economic, and political impacts of scientific innovation.

Histories of science were originally written by practicing and retired scientists, starting primarily with William Whewell, as a way to communicate the virtues of science to the public. In the early 1930s, after a famous paper given by the Soviet historian Boris Hessen, was focused into looking at the ways in which scientific practices were allied with the needs and motivations of their context. After World War II, extensive resources were put into teaching and researching the discipline, with the hopes that it would help the public better understand both Science and Technology as they came to play an exceedingly prominent role in the world. In the 1960s, especially in the wake of the work done by Thomas Kuhn, the discipline began to serve a very different function, and began to be used as a way to critically examine the scientific enterprise.

Academic discipline

As an academic field, history of science and technology began with the publication of William Whewell's *History of the Inductive Sciences* (first published in 1837). A more formal study of the history of science as an independent discipline was launched by George Sarton's publications, *Introduction to the History of Science* (1927) and the *Isis* journal (founded in 1912). Sarton exemplified the early 20th-century view of the history of science as the history of great men and great ideas. He shared with many of his contemporaries a Whiggish belief in history as a record of the advances and delays in the march of progress. The history of science was not a recognized subfield of American history in this period, and most of the work was carried out by interested scientists and physicians rather than professional historians. With the work of I. Bernard Cohen at Harvard, the history of science became an established subdiscipline of history after 1945.

The history of mathematics, history of technology, and history of philosophy are distinct areas of research and are covered in other articles. Mathematics is closely related to but distinct from natural science (at least in the modern conception). Technology is likewise closely related to but clearly differs from the search for empirical truth.

History of science is an academic discipline, with an international community of specialists. Main professional organizations for this field include the History of Science Society, the British Society for the History of Science, and the European Society for the History of Science.

Much of the study of the history of science has been devoted to answering questions about what science *is*, how it *functions*, and whether it exhibits large-scale patterns and trends. The sociology of science in particular has focused on the ways in which scientists work, looking closely at the ways in which they "produce" and "construct" scientific knowledge. Since the 1960s, a common trend in science studies (the study of the sociology and history of science) has been to emphasize the "human component" of scientific knowledge, and to de-emphasize the view that scientific data are self-evident, value-free, and context-free. The field of Science and Technology Studies, an area that overlaps and often informs historical studies of science, focuses on the social context of science in both contemporary and historical periods.

Humboldtian science refers to the early 19th century approach of combining scientific field work with the age of Romanticism sensitivity, ethics and aesthetic ideals. It helped to install natural history as a separate field, gave base for ecology and was based on the role model of scientist, naturalist and explorer Alexander von Humboldt. The later 19th century positivism asserted that all authentic knowledge allows verification and that all authentic knowledge assumes that the only valid knowledge is scientific.

A major subject of concern and controversy in the philosophy of science has been the nature of *theory change* in science. Karl Popper argued that scientific knowledge is progressive and cumulative; Thomas Kuhn, that scientific knowledge moves through "paradigm shifts" and is not necessarily progressive; and Paul Feyerabend, that scientific knowledge is not cumulative or progressive and that there can be no demarcation in terms of method between science and any other form of investigation.

The mid 20th century saw a series of studies relying to the role of science in a social context, starting from Thomas Kuhn's *The Structure of Scientific Revolutions* in 1962. It opened the study of science to new disciplines by suggesting that the evolution of science was in part sociologically determined and that positivism did not explain the actual interactions and strategies of the human participants in science. As Thomas Kuhn put it, the history of science may be seen in more nuanced terms, such as that of competing paradigms or conceptual systems in a wider matrix that includes intellectual, cultural, economic and political themes outside of science. "Partly by selection and partly by distortion, the scientists of earlier ages are implicitly presented as having worked upon the same set of fixed problems and in accordance with the same set of fixed canons that the most recent revolution in scientific theory and method made seem scientific."

Further studies, e.g. Jerome Ravetz 1971 *Scientific Knowledge and its Social Problems* referred to the role of the scientific community, as a social construct, in accepting or rejecting (objective) scientific knowledge. The Science wars of the 1990s were about the influence of especially French philosophers, which denied the objectivity of science in general or seemed to do so. They described as well differences between the idealized model of a pure science and the actual scientific practice; while scientism, a revival of the positivism approach, saw in precise measurement and rigorous calculation the basis for finally settling enduring metaphysical and moral controversies.

However, more recently some of the leading critical theorists have recognized that their postmodern deconstructions have at times been counter-productive, and are providing intellectual ammunition for reactionary interests. Bruno Latour noted that "dangerous extremists are using the very same argument of social construction to destroy hard-won evidence that could save our lives. Was I wrong to participate in the invention of this field known as science studies? Is it enough to say that we did not really mean what we meant?"

Universities with HST programs

Argentina

- Buenos Aires Institute of Technology, Argentina, has been offering courses on History of the Technology and the Science.
- National Technological University, Argentina, has a complete history program on its offered careers.

Australia

- The University of Sydney offers both undergraduate and postgraduate programmes in the History and Philosophy of Science, run by the Unit for the History and Philosophy of Science, within the Science Faculty. Undergraduate coursework can be completed as part of either a Bachelor of Science or a Bachelor of Arts Degree. Undergraduate study can be furthered by completing an additional Honours year. For postgraduate study, the Unit offers both coursework and research based degrees. The two course-work based postgraduate degrees are the Graduate Certificate in Science (HPS) and the Graduate Diploma in Science (HPS). The two research based postgraduate degrees are a Master of Science (MSc) and Doctor of Philosophy (PhD).

Belgium

- University of Liège, has a Department called Centre d'histoire des Sciences et Techniques.

Canada

- Carleton University Ottawa offer courses in Ancient Science and Technology in its Technology, Society and Environment program.
- University of Toronto has a program in History and Philosophy of Science and Technology.
- University of King's College in Halifax, Nova Scotia has a History of Science and Technology Program.

France

- Nantes University has a dedicated Department called Centre François Viète.
- Paris Diderot University (Paris 7) has a Department of History and Philosophy of Science.
- A CNRS research center in History and Philosophy of Science SPHERE, affiliated with Paris Diderot

University, has a dedicated history of technology section.

- Pantheon-Sorbonne University (Paris 1) has a dedicated Institute of History and Philosophy of Science and Technics.
- The École Normale Supérieure de Paris has a history of science Department.

Germany

- Technische Universität Berlin, has a program in the History of Science and Technology.

Greece

- The University of Athens has a Department of Philosophy and History of Science

India

History of science and technology is a well developed field in India. At least three generations of scholars can be identified. The first generation includes D.D.Kosambi, Dharmpal, Debiprasad Chattopadhyay and Rahman. The second generation mainly consists of Ashis Nandy, Deepak Kumar, Dhruv Raina, S. Irfan Habib, Shiv Visvanathan, Gyan Prakash, Stan Lourdswamy, V.V. Krishna, Itty Abraham, Richard Grove, Kavita Philip, Mira Nanda and Rob Anderson. There is an emergent third generation that includes scholars like Abha Sur and Jahnavi Phalkey.

Departments and Programmes

The National Institute of Science, Technology and Development Studies had a research group active in the 1990s which consolidated social history of science as a field of research in India. Currently there are several institutes and university departments offering HST programmes.

- Jawaharlal Nehru University has an Mphil-PhD program that offer specialisation in Social History of Science. It is at the History of Science and Education group of the Zakir Husain Centre for Educational Studies (ZHCES) in the School of Social Sciences. Renowned Indian science historians Deepak Kumar and Dhruv Raina teach here. Also, *Centre for Studies in Science Policy has an Mphil-PhD program that offers specialization in Science, Technology, and Society along with various allied subdisciplines.
- Central University of Gujarat has an MPhil-PhD programme in Studies in Science, Technology & Innovation Policy at the Centre for Studies in Science, Technology & Innovation Policy (CSSTIP), where Social History of Science and Technology in India is a major emphasis for research and teaching.
- Banaras Hindu University has programs: one in History of Science and Technology at the Faculty of Science and one in Historical and Comparative Studies of the Sciences and the Humanities at the Faculty of Humanities.
- Andhra University has now set History of Science and Technology as a compulsory subject for all the First year B-Tech students.

Israel

- Tel Aviv University. The Cohn Institute for the History and Philosophy of Science and Ideas is a research and graduate teaching institute within the framework of the School of History of Tel Aviv University.
- Bar-Ilan University has a graduate program in Science, Technology, and Society.

Japan

- Kyoto University has a program in the Philosophy and History of Science.
- Tokyo Institute of Technology has a program in the History, Philosophy, and Social Studies of Science and Technology.
- The University of Tokyo has a program in the History and Philosophy of Science.

Netherlands

- Utrecht University, has two co-operating programs: one in History and Philosophy of Science at the Faculty of Natural Sciences and one in Historical and Comparative Studies of the Sciences and the Humanities at the Faculty of Humanities.

Russia

Spain

- University of the Basque Country, offers a master's degree and PhD programme in History and Philosophy of Science and runs since 1952 *THEORIA. International Journal for Theory, History and Foundations of Science*. The university also sponsors the Basque Museum of the History of Medicine and Science, the only open museum of History of Science of Spain, that in the past offered also PhD courses.
- Universitat Autònoma de Barcelona, offers a master's degree and PhD programme in HST together with the Universitat de Barcelona.
- Universitat de València, offers a master's degree and PhD programme in HST together with the Consejo Superior de Investigaciones Científicas.

Sweden

- Linköpings universitet, has a Science, Technology, and Society program which includes HST.

Switzerland

- University of Bern, has an undergraduate and a graduate program in the History and Philosophy of Science.

Ukraine

- State University of Infrastructure and Technologies, has a Department of Philosophy and History of Science and technology.

United Kingdom

- University of Kent has a Centre for the History of the Sciences, which offers Masters programmes and undergraduate modules.
- University College London's Department of Science and Technology Studies offers undergraduate programme in History and Philosophy of Science, including two BSc single honour degrees (UCAS V550 and UCAS L391), plus both major and minor streams in history, philosophy and social studies of science in UCL's Natural Sciences programme. The department also offers MSc degrees in History and Philosophy of Science and in the study of contemporary Science, Technology, and Society. An MPhil/PhD research degree is offered, too. UCL also contains a Centre for the History of Medicine. This operates a small teaching programme in History of Medicine.
- University of Oxford has a one-year graduate course in 'History of Science: Instruments, Museums, Science, Technology' associated with the Museum of the History of Science.
- University of Leeds has both undergraduate and graduate programmes in History and Philosophy of Science in the Department of Philosophy.

- University of Manchester offers undergraduate modules and postgraduate study in History of Science, Technology and Medicine and is sponsored by the Wellcome Trust.
- University of Bristol has a masters and PhD program in the Philosophy and History of Science.
- University of Cambridge has an undergraduate course and a large masters and PhD program in the History and Philosophy of Science (including the History of Medicine).
- University of Durham has several undergraduate History of Science modules in the Philosophy department, as well as Masters and PhD programs in the discipline.
- London Centre for the History of Science, Medicine, and Technology - this Centre closes in 2013. It was formed in 1987 and ran a taught MSc programme, jointly taught by University College London's Department of Science and Technology Studies and Imperial College London. The Masters programme transferred to UCL.

United States

Academic study of the history of science as an independent discipline was launched by George Sarton at Harvard with his book *Introduction to the History of Science* (1927) and the *Isis* journal (founded in 1912). Sarton exemplified the early 20th century view of the history of science as the history of great men and great ideas. He shared with many of his contemporaries a Whiggish belief in history as a record of the advances and delays in the march of progress. The History of Science was not a recognized subfield of American history in this period, and most of the work was carried out by interested Scientists and Physicians rather than professional Historians. With the work of I. Bernard Cohen at Harvard, the history of Science became an established subdiscipline of history after 1945.

- Arizona State University's Center for Biology and Society offers several paths for MS or PhD students who are interested in issues surrounding the history and philosophy of the science, particularly biological sciences. The strength of the center has much to do with the success of its director Jane Maienschein. With a concentration in Biology and Society one can focus on History and Philosophy of Science, Bioscience Ethics, Policy and Law, or Ecology, Economics, and Ethics of the Environment.
- Brown University has a program in Science and Technology Studies and the History of Mathematics. (This program is in the process of being phased out. There are no longer any full-time faculty, and no new students are being admitted to the program.)
- California Institute of Technology offers courses in the History and Philosophy of Science to fulfill its core humanities requirements.
- Case Western Reserve University has an undergraduate interdisciplinary program in the History and Philosophy of Science and a graduate program in the History of Science, Technology, Environment, and Medicine (STEM).

- Cornell University offers a variety of courses within the Science and Technology course. One notable course is called Science and Technology History, taught currently by Professor Peter Dear, which centers upon the development of Science and Technology History from the Newtonian era up to the Einsteinian revolution. This class is one of the longest running classes at Cornell University and is offered by the College of Arts and Sciences and caters to students who want to learn more about the development of modern science.
- Georgia Institute of Technology has an undergraduate and graduate program in the History of Technology and Society.
- Harvard has a large undergraduate and graduate program in History of Science, and is one of the largest departments currently in the world.
- Indiana University offers undergraduate courses and a masters and PhD program in the History and Philosophy of Science.
- Johns Hopkins University has an undergraduate and graduate program in the History of Science, Medicine, and Technology.
- University of Kings College has a degree program in History of Science and Technology
- Lehigh University offers an undergraduate level STS concentration (founded in 1972) and a graduate program with emphasis on the History of Industrial America.
- Massachusetts Institute of Technology has a Science, Technology, and Society program which includes HST.

- Michigan State University offers an undergraduate major and minor in History, Philosophy, and Sociology of Science through its Lyman Briggs College.
- New Jersey Institute of Technology has a Science, Technology, and Society program which includes the History of Science and Technology
- Oregon State University offers a Masters and Ph.D. in History of Science through its Department of History.
- Princeton University has a program in the History of Science.
- Rensselaer Polytechnic Institute has a Science and Technology Studies department
- Rutgers has a graduate Program in History of Science, Technology, Environment, and Health.
- Stanford has a History and Philosophy of Science and Technology program.
- Stevens Institute of Technology has an undergraduate and graduate program in the History of Science.
- University of California, Berkeley offers a graduate degree in HST through its History program, and maintains a separate sub-department for the field.
- University of California, Los Angeles has a relatively large group History of Science and Medicine faculty and graduate students within its History department, and also offers an undergraduate minor in the History of Science.
- University of California Santa Barbara has an interdisciplinary graduate program emphasis in Technology & Society through the Center for

Information Technology & Society. The history department is affiliated with the emphasis.

- University of Florida has a Graduate Program in 'History of Science, Technology, and Medicine' at the University of Florida provides undergraduate and graduate degrees.
- University of Minnesota has a Ph.D. program in History of Science, Technology, and Medicine as well as undergraduate courses in these fields. The Minnesota model "integrates" historians of science, technology, and medicine within the various science departments they study, each holding a joint appointment.
- University of Oklahoma has an undergraduate minor and a graduate degree program in History of Science.
- University of Pennsylvania has a program in History and Sociology of Science.
- University of Pittsburgh's Department of History and Philosophy of Science offers graduate and undergraduate courses.
- University of Puget Sound has a Science, Technology, and Society program, which includes the history of Science and Technology.
- University of Wisconsin–Madison has one of the largest programs in History of Science, Medicine and Technology, with particular strength in Medical History, History of Biology, History of Science and Religion, and Environmental History. This program was the first to exist as an independent academic department. It offers M.A. and Ph.D. degrees as well as an undergraduate major.

- Wesleyan University has a Science in Society program.
- Yale University has a program in the History of Science and Medicine.

Prominent historians of the field

See also the list of George Sarton medalists.

- Wiebe Bijker
- Peter J. Bowler
- Janet Browne
- Stephen G. Brush
- James Burke
- Edwin Arthur Burtt (1892–1989)
- Johann Beckmann (1739–1811)
- Jim Bennett
- Herbert Butterfield (1900–1979)
- Martin Campbell-Kelly
- Georges Canguilhem (1904–1995)
- Allan Chapman
- I. Bernard Cohen (1914–2003)
- A. C. Crombie (1915–1996)
- E. J. Dijksterhuis (1892–1965)
- Pierre Duhem (1861–1916)
- A. Hunter Dupree (1921–2019)
- George Dyson
- Jacques Ellul (1912–1994)
- Eugene S. Ferguson (1916–2004)
- Peter Galison
- Sigfried Giedion

- Charles Coulston Gillispie
- Robert Gunther (1869–1940)
- Paul Forman
- Donna Haraway
- Peter Harrison
- Ahmad Y Hassan
- John L. Heilbron
- Boris Hessen
- Reijer Hooykaas
- David A. Hounshell
- Thomas P. Hughes
- Evelyn Fox Keller
- Daniel Kevles
- Alexandre Koyré (1892–1964)
- Melvin Kranzberg
- Thomas Kuhn
- Deepak Kumar
- Gilbert LaFreniere
- Bruno Latour
- David C. Lindberg
- G. E. R. Lloyd
- Jane Maienschein
- Anneliese Maier
- Leo Marx
- Lewis Mumford (1895–1990)
- John E. Murdoch (1927-2010)
- Otto Neugebauer (1899–1990)
- William R. Newman
- David Noble
- Ronald Numbers
- David E. Nye
- Abraham Pais (1918–2000)

- Trevor Pinch
- Theodore Porter
- Lawrence M. Principe
- Raúl Rojas
- Michael Ruse
- A. I. Sabra
- Jan Sapp
- George Sarton (1884–1956)
- Simon Schaffer
- Howard Segal (1948–2020)
- Steven Shapin
- Wolfgang Schivelbusch
- Charles Singer (1876–1960)
- Merritt Roe Smith
- Stephen Snobelen
- M. Norton Wise
- Frances A. Yates (1899–1981)

Chapter 18

History of Earth

The **history of Earth** concerns the development of planet Earth from its formation to the present day. Nearly all branches of natural science have contributed to understanding of the main events of Earth's past, characterized by constant geological change and biological evolution.

The geological time scale (GTS), as defined by international convention, depicts the large spans of time from the beginning of the Earth to the present, and its divisions chronicle some definitive events of Earth history. (In the graphic, Ma means "million years ago".) Earth formed around 4.54 billion years ago, approximately one-third the age of the universe, by accretion from the solar nebula. Volcanic outgassing probably created the primordial atmosphere and then the ocean, but the early atmosphere contained almost no oxygen. Much of the Earth was molten because of frequent collisions with other bodies which led to extreme volcanism. While the Earth was in its earliest stage (Early Earth), a giant impact collision with a planet-sized body named Theia is thought to have formed the Moon. Over time, the Earth cooled, causing the formation of a solid crust, and allowing liquid water on the surface.

The Hadean eon represents the time before a reliable (fossil) record of life; it began with the formation of the planet and ended 4.0 billion years ago. The following Archean and Proterozoic eons produced the beginnings of life on Earth and its earliest evolution. The succeeding eon is the Phanerozoic, divided into three eras: the Palaeozoic, an era of arthropods, fishes, and the first life on land; the Mesozoic, which spanned the rise, reign, and climactic extinction of the non-avian dinosaurs; and the Cenozoic, which saw the rise of mammals. Recognizable humans emerged at most 2 million years ago, a vanishingly small period on the geological scale.

The earliest undisputed evidence of life on Earth dates at least from 3.5 billion years ago, during the Eoarchean Era, after a geological crust started to solidify following the earlier molten Hadean Eon. There are microbial mat fossils such as stromatolites found in 3.48 billion-year-old sandstone discovered in Western Australia. Other early physical evidence of a biogenic substance is graphite in 3.7 billion-year-old metasedimentary rocks discovered in southwestern Greenland as well as "remains of biotic life" found in 4.1 billion-year-old rocks in Western Australia. According to one of the researchers, "If life arose relatively quickly on Earth ... then it could be common in the universe."

Photosynthetic organisms appeared between 3.2 and 2.4 billion years ago and began enriching the atmosphere with oxygen. Life remained mostly small and microscopic until about 580 million years ago, when complex multicellular life arose, developed over time, and culminated in the Cambrian Explosion about 541 million years ago. This sudden diversification of life forms produced most of the major phyla known today, and divided the Proterozoic Eon from the Cambrian Period of the Paleozoic Era. It is estimated that 99 percent of all species that ever lived on Earth, over five billion, have gone extinct. Estimates on the number of Earth's current species range from 10 million to 14 million, of which about 1.2 million are documented, but over 86 percent have not been described. However, it was recently claimed that 1 trillion species currently live on Earth, with only one-thousandth of one percent described.

The Earth's crust has constantly changed since its formation, as has life since its first appearance. Species continue to evolve, taking on new forms, splitting into daughter species, or going extinct in the face of ever-changing physical environments. The process of plate tectonics continues to shape the Earth's continents and oceans and the life they harbor.

Eons

In geochronology, time is generally measured in mya (million years ago), each unit representing the period of approximately 1,000,000 years in the past. The history of Earth is divided into four great eons, starting 4,540 mya with the formation of the planet. Each eon saw the most significant changes in Earth's composition, climate and life. Each eon is subsequently divided into eras, which in turn are divided into periods, which are further divided into epochs.

Geologic time scale

- The history of the Earth can be organized chronologically according to the geologic time scale, which is split into intervals based on stratigraphic analysis. The following five timelines show the geologic time scale. The first shows the entire time from the formation of the Earth to the present, but this gives little space for the most recent eon. Therefore, the second timeline shows an expanded view of the most recent eon. In a similar way, the most recent era is expanded in the third timeline, the most recent period is expanded in the fourth timeline, and the most recent epoch is expanded in the fifth timeline.

Solar System formation

The standard model for the formation of the Solar System (including the Earth) is the solar nebula hypothesis. In this model, the Solar System formed from a large, rotating cloud of interstellar dust and gas called the solar nebula. It was composed of hydrogen and helium created shortly after the Big Bang 13.8 Ga (billion years ago) and heavier elements ejected by supernovae. About 4.5 Ga, the nebula began a contraction that may have been triggered by the shock wave from a nearby supernova. A shock wave would have also made the nebula rotate. As the cloud began to accelerate, its angular momentum, gravity, and inertia flattened it into a protoplanetary disk perpendicular to its axis of rotation. Small perturbations due to collisions and the angular momentum of other large debris created the means by which kilometer-sized protoplanets began to form, orbiting the nebular center.

The center of the nebula, not having much angular momentum, collapsed rapidly, the compression heating it until nuclear fusion of hydrogen into helium began. After more contraction, a T Tauri star ignited and evolved into the Sun. Meanwhile, in the outer part of the nebula gravity caused matter to condense around density perturbations and dust particles, and the rest of the protoplanetary disk began separating into rings. In a process known as runaway accretion, successively larger fragments of dust and debris clumped together to form planets. Earth formed in this manner about 4.54 billion years ago (with an uncertainty of 1%) and was largely completed within 10–20 million years. The solar wind of the newly formed T Tauri star cleared out most of the material in the disk that had not already condensed into larger bodies. The same process is expected to produce accretion disks around virtually all newly forming stars in the universe, some of which yield planets.

The proto-Earth grew by accretion until its interior was hot enough to melt the heavy, siderophile metals. Having higher densities than the silicates, these metals sank. This so-called *iron catastrophe* resulted in the separation of a primitive mantle and a (metallic) core only 10 million years after the Earth began to form, producing the layered structure of Earth and setting up the formation of Earth's magnetic field. J.A. Jacobs wasthe first to suggest that Earth's inner core—a solid center distinct from the liquid outer core—is freezing and growing out of the liquid outer core due to the gradual cooling of Earth's interior (about 100 degrees Celsius per billion years).

Hadean and Archean Eons

The first eon in Earth's history, the *Hadean*, begins with the Earth's formation and is followed by the *Archean* eon at 3.8 Ga. The oldest rocks found on Earth date to about 4.0 Ga, and the oldest detrital zircon crystals in rocks to about 4.4 Ga, soon after the formation of the Earth's crust and the Earth itself. The giant impact hypothesis for the Moon's formation states that shortly after formation of an initial crust, the proto-Earth was impacted by a smaller protoplanet, which ejected part of the mantle and crust into space and created the Moon.

From crater counts on other celestial bodies, it is inferred that a period of intense meteorite impacts, called the *Late Heavy Bombardment*, began about 4.1 Ga, and concluded around 3.8 Ga, at the end of the Hadean. In addition, volcanism was severe due to the large heat flow and geothermal gradient. Nevertheless, detrital zircon crystals dated to 4.4 Ga show evidence of having undergone contact with liquid water, suggesting that the Earth already had oceans or seas at that time.

By the beginning of the Archean, the Earth had cooled significantly. Present life forms could not have survived at Earth's surface, because the Archean atmosphere lacked oxygen hence had no ozone layer to block ultraviolet light. Nevertheless, it is believed that primordial life began to evolve by the early Archean, with candidate fossils dated to around 3.5 Ga. Some scientists even speculate that life could have begun during the early Hadean, as far back as 4.4 Ga, surviving the possible Late Heavy Bombardment period in hydrothermal vents below the Earth's surface.

Formation of the Moon

Earth's only natural satellite, the Moon, is larger relative to its planet than any other satellite in the Solar System. During the Apollo program, rocks from the Moon's surface were brought to Earth. Radiometric dating of these rocks shows that the Moon is 4.53 ± 0.01 billion years old, formed at least 30 million years after the Solar System. New evidence suggests the Moon formed even later, 4.48 ± 0.02 Ga, or 70–110 million years after the start of the Solar System.

Theories for the formation of the Moon must explain its late formation as well as the following facts. First, the Moon has a low density (3.3 times that of water, compared to 5.5 for the Earth) and a small metallic core. Second, there is virtually no water or other volatiles on the Moon. Third, the Earth and Moon have the same oxygen isotopic signature (relative abundance of the oxygen isotopes). Of the theories proposed to account for these phenomena, one is widely accepted: The *giant impact hypothesis* proposes that the Moon originated after a body the size of Mars (sometimes named Theia) struck the proto-Earth a glancing blow.

The collision released about 100 million times more energy than the more recent Chicxulub impact that is believed to have caused the extinction of the non-avian dinosaurs. It was enough to vaporize some of the Earth's outer layers and melt both bodies. A portion of the mantle material was ejected into orbit around the Earth. The giant impact hypothesis predicts that the Moon was depleted of metallic material, explaining its abnormal composition. The ejecta in orbit around the Earth could have condensed into a single body within a couple of weeks. Under the influence of its own gravity, the ejected material became a more spherical body: the Moon.

First continents

Mantle convection, the process that drives plate tectonics, is a result of heat flow from the Earth's interior to the Earth's surface. It involves the creation of rigid tectonic plates at mid-oceanic ridges. These plates are destroyed by subduction into the mantle at subduction zones. During the early Archean (about 3.0 Ga) the mantle was much hotter than today, probably around 1,600 °C (2,910 °F), so convection in the mantle was faster. Although a process similar to present-day plate tectonics did occur, this would have gone faster too. It is likely that during the Hadean and Archean, subduction zones were more common, and therefore tectonic plates were smaller.

The initial crust, formed when the Earth's surface first solidified, totally disappeared from a combination of this fast Hadean plate tectonics and the intense impacts of the Late Heavy Bombardment. However, it is thought that it was basaltic in composition, like today's oceanic crust, because little crustal differentiation had yet taken place. The first larger pieces of continental crust, which is a product of differentiation of lighter elements during partial melting in the lower crust, appeared at the end of the Hadean, about 4.0 Ga. What is left of these first small continents are called cratons. These pieces of late Hadean and early Archean crust form the cores around which today's continents grew.

The oldest rocks on Earth are found in the North American craton of Canada. They are tonalites from about 4.0 Ga. They show traces of metamorphism by high temperature, but also sedimentary grains that have been rounded by erosion during transport by water, showing that rivers and seas existed then. Cratons consist primarily of two alternating types of terranes. The first are so-called greenstone belts, consisting of low-grade metamorphosed sedimentary rocks. These "greenstones" are similar to the sediments today found in oceanic trenches, above subduction zones. For this reason, greenstones are sometimes seen as evidence for subduction during the Archean. The second type is a complex of felsic magmatic rocks. These rocks are mostly tonalite, trondhjemite or granodiorite, types of rock similar in composition to granite (hence such terranes are called TTG-terranes). TTG-complexes are seen as the relicts of the first continental crust, formed by partial melting in basalt.

Oceans and atmosphere

Earth is often described as having had three atmospheres. The first atmosphere, captured from the solar nebula, was composed of light (atmophile) elements from the solar nebula, mostly hydrogen and helium. A combination of the solar wind and Earth's heat would have driven off this atmosphere, as a result of which the atmosphere is now depleted of these elements compared to cosmic abundances. After the impact which created the Moon, the molten Earth released volatile gases; and later more gases were released by volcanoes, completing a second atmosphere rich in greenhouse gases but poor in oxygen. Finally, the third atmosphere, rich in oxygen, emerged when bacteria began to produce oxygen about 2.8 Ga.

In early models for the formation of the atmosphere and ocean, the second atmosphere was formed by outgassing of volatiles from the Earth's interior. Now it is considered likely that many of the volatiles were delivered during accretion by a process known as *impact degassing* in which incoming bodies vaporize on impact. The ocean and atmosphere would, therefore, have started to form even as the Earth formed. The new atmosphere probably contained water vapor, carbon dioxide, nitrogen, and smaller amounts of other gases.

Planetesimals at a distance of 1 astronomical unit (AU), the distance of the Earth from the Sun, probably did not contribute any water to the Earth because the solar nebula was too hot for ice to form and the hydration of rocks by water vapor would have taken too long. The water must have been supplied by meteorites from the outer asteroid belt and some large planetary embryos from beyond 2.5 AU. Comets may also have contributed. Though most comets are today in orbits farther away from the Sun than Neptune, computer simulations show that they were originally far more common in the inner parts of the Solar System.

As the Earth cooled, clouds formed. Rain created the oceans. Recent evidence suggests the oceans may have begun forming as early as 4.4 Ga. By the start of the Archean eon, they already covered much of the Earth. This early formation has been difficult to explain because of a problem known as the faint young Sun paradox. Stars are known to get brighter as they age, and at the time of its formation the Sun would have been emitting only 70% of its current power. Thus, the Sun has become 30% brighter in the last 4.5 billion years. Many models indicate that the Earth would have been covered in ice. A likely solution is that there was enough carbon dioxide and methane to produce a greenhouse effect. The carbon dioxide would have been produced by volcanoes and the methane by early microbes. Another greenhouse gas, ammonia, would have been ejected by volcanos but quickly destroyed by ultraviolet radiation.

Origin of life

One of the reasons for interest in the early atmosphere and ocean is that they form the conditions under which life first arose. There are many models, but little consensus, on how life emerged from non-living chemicals; chemical systems created in the laboratory fall well short of the minimum complexity for a living organism.

The first step in the emergence of life may have been chemical reactions that produced many of the simpler organic compounds, including nucleobases and amino acids, that are the building blocks of life. An experiment in 1953 by Stanley Miller and Harold Urey showed that such molecules could form in an atmosphere of water, methane, ammonia and hydrogen with the aid of sparks to mimic the effect of lightning. Although atmospheric composition was probably different from that used by Miller and Urey, later experiments with more realistic compositions also managed to synthesize organic molecules. Computer simulations show that extraterrestrial organic molecules could have formed in the protoplanetary disk before the formation of the Earth.

Additional complexity could have been reached from at least three possible starting points: self-replication, an organism's ability to produce offspring that are similar to itself; metabolism, its ability to feed and repair itself; and external cell membranes, which allow food to enter and waste products to leave, but exclude unwanted substances.

Replication first: RNA world

Even the simplest members of the three modern domains of life use DNA to record their "recipes" and a complex array of RNA and protein molecules to "read" these instructions and use them for growth, maintenance, and self-replication.

The discovery that a kind of RNA molecule called a ribozyme can catalyze both its own replication and the construction of proteins led to the hypothesis that earlier life-forms were based entirely on RNA. They could have formed an RNA world in which there were individuals but no species, as mutations and horizontal gene transfers would have meant that the offspring in each generation were quite likely to have different genomes from those that their parents started with. RNA would later have been replaced by DNA, which is more stable and therefore can build longer genomes, expanding the range of capabilities a single organism can have. Ribozymes remain as the main components of ribosomes, the "protein factories" of modern cells.

Although short, self-replicating RNA molecules have been artificially produced in laboratories, doubts have been raised about whether natural non-biological synthesis of RNA is possible. The earliest ribozymes may have been formed of simpler nucleic acids such as PNA, TNA or GNA, which would have been replaced later by RNA. Other pre-RNA replicators have been posited, including crystals and even quantum systems.

In 2003 it was proposed that porous metal sulfide precipitates would assist RNA synthesis at about 100 °C (212 °F) and at ocean-bottom pressures near hydrothermal vents. In this hypothesis, the proto-cells would be confined in the pores of the metal substrate until the later development of lipid membranes.

Metabolism first: iron–sulfur world

Another long-standing hypothesis is that the first life was composed of protein molecules. Amino acids, the building blocks of proteins, are easily synthesized in plausible prebiotic conditions, as are small peptides (polymers of amino acids) that make good catalysts. A series of experiments starting in 1997 showed that amino acids and peptides could form in the presence of carbon monoxide and hydrogen sulfide with iron sulfide and nickel sulfide as catalysts. Most of the steps in their assembly required temperatures of about 100 °C (212 °F) and moderate pressures, although one stage required 250 °C (482 °F) and a pressure equivalent to that found under 7 kilometers (4.3 mi) of rock. Hence, self-sustaining synthesis of proteins could have occurred near hydrothermal vents.

A difficulty with the metabolism-first scenario is finding a way for organisms to evolve. Without the ability to replicate as individuals, aggregates of molecules would have "compositional genomes" (counts of molecular species in the aggregate) as the target of natural selection. However, a recent model shows that such a system is unable to evolve in response to natural selection.

Membranes first: Lipid world

It has been suggested that double-walled "bubbles" of lipids like those that form the external membranes of cells may have been an essential first step. Experiments that simulated the conditions of the early Earth have reported the formation of lipids, and these can spontaneously form liposomes, double-walled "bubbles", and then reproduce themselves. Although they are not intrinsically information-carriers as nucleic acids are, they would be subject to natural selection for longevity and reproduction. Nucleic acids such as RNA might then have formed more easily within the liposomes than they would have outside.

The clay theory

- Some clays, notably montmorillonite, have properties that make them plausible accelerators for the emergence of an RNA world: they grow by self-replication of their crystalline pattern, are subject to an analog of natural selection (as the clay "species" that grows fastest in a particular environment rapidly becomes dominant), and can catalyze the formation of RNA molecules. Although this idea has not become the scientific consensus, it still has active supporters.

Research in 2003 reported that montmorillonite could also accelerate the conversion of fatty acids into "bubbles", and that the bubbles could encapsulate RNA attached to the clay. Bubbles can then grow by absorbing additional lipids and dividing. The formation of the earliest cells may have been aided by similar processes.

A similar hypothesis presents self-replicating iron-rich clays as the progenitors of nucleotides, lipids and amino acids.

Last universal common ancestor

It is believed that of this multiplicity of protocells, only one line survived. Current phylogenetic evidence suggests that the last universal ancestor (LUA) lived during the early Archean eon, perhaps 3.5 Ga or earlier. This LUA cell is the ancestor of all life on Earth today. It was probably a prokaryote, possessing a cell membrane and probably ribosomes, but lacking a nucleus or membrane-bound organelles such as mitochondria or chloroplasts. Like modern cells, it used DNA as its genetic code, RNA for information transfer and protein synthesis, and enzymes to catalyze reactions. Some scientists believe that instead of a single organism being the last universal common ancestor, there were populations of organisms exchanging genes by lateral gene transfer.

Proterozoic Eon

The Proterozoic eon lasted from 2.5 Ga to 542 Ma (million years) ago. In this time span, cratons grew into continents with modern sizes. The change to an oxygen-rich atmosphere was a crucial development. Life developed from prokaryotes into eukaryotes and multicellular forms. The Proterozoic saw a couple of severe ice ages called snowball Earths. After the last Snowball Earth about 600 Ma, the evolution of life on Earth accelerated. About 580 Ma, the Ediacaran biota formed the prelude for the Cambrian Explosion.

Oxygen revolution

The earliest cells absorbed energy and food from the surrounding environment. They used fermentation, the breakdown of more complex compounds into less complex compounds with less energy, and used the energy so liberated to grow and reproduce. Fermentation can only occur in an *anaerobic* (oxygen-free) environment. The evolution of photosynthesis made it possible for cells to derive energy from the Sun.

Most of the life that covers the surface of the Earth depends directly or indirectly on photosynthesis. The most common form, oxygenic photosynthesis, turns carbon dioxide, water, and sunlight into food. It captures the energy of sunlight in energy-rich molecules such as ATP, which then provide the energy to make sugars. To supply the electrons in the circuit, hydrogen is stripped from water, leaving oxygen as a waste product. Some organisms, including purple bacteria and green sulfur bacteria, use an anoxygenic form of photosynthesis that uses alternatives to hydrogen stripped from water as electron donors; examples are hydrogen sulfide, sulfur and iron. Such extremophile organisms are restricted to otherwise inhospitable environments such as hot springs and hydrothermal vents.

The simpler anoxygenic form arose about 3.8 Ga, not long after the appearance of life. The timing of oxygenic photosynthesis is more controversial; it had certainly appeared by about 2.4 Ga, but some researchers put it back as far as 3.2 Ga. The latter "probably increased global productivity by at least two or three orders of magnitude". Among the oldest remnants of oxygen-producing lifeforms are fossil stromatolites.

At first, the released oxygen was bound up with limestone, iron, and other minerals. The oxidized iron appears as red layers in geological strata called banded iron formations that formed in abundance during the Siderian period (between 2500 Ma and 2300 Ma). When most of the exposed readily reacting minerals were oxidized, oxygen finally began to accumulate in the atmosphere. Though each cell only produced a minute amount of oxygen, the combined metabolism of many cells over a vast time transformed Earth's atmosphere to its current state. This was Earth's third atmosphere.

Some oxygen was stimulated by solar ultraviolet radiation to form ozone, which collected in a layer near the upper part of the atmosphere. The ozone layer absorbed, and still absorbs, a significant amount of the ultraviolet radiation that once had passed through the atmosphere. It allowed cells to colonize the surface of the ocean and eventually the land: without the ozone layer, ultraviolet radiation bombarding land and sea would have caused unsustainable levels of mutation in exposed cells.

Photosynthesis had another major impact. Oxygen was toxic; much life on Earth probably died out as its levels rose in what is known as the *oxygen catastrophe*. Resistant forms survived and thrived, and some developed the ability to use oxygen to increase their metabolism and obtain more energy from the same food.

Snowball Earth

The natural evolution of the Sun made it progressively more luminous during the Archean and Proterozoic eons; the Sun's luminosity increases 6% every billion years. As a result, the Earth began to receive more heat from the Sun in the Proterozoic eon. However, the Earth did not get warmer. Instead, the geological record suggests it cooled dramatically during the early Proterozoic. Glacial deposits found in South Africa date back to 2.2 Ga, at which time, based on paleomagnetic evidence, they must have been located near the equator. Thus, this glaciation, known as the Huronian glaciation, may have been global. Some scientists suggest this was so severe that the Earth was frozen over from the poles to the equator, a hypothesis called Snowball Earth.

The Huronian ice age might have been caused by the increased oxygen concentration in the atmosphere, which caused the decrease of methane (CH_4) in the atmosphere. Methane is a strong greenhouse gas, but with oxygen it reacts to form CO_2, a less effective greenhouse gas. When free oxygen became available in the atmosphere, the concentration of methane could have decreased dramatically, enough to counter the effect of the increasing heat flow from the Sun.

However, the term Snowball Earth is more commonly used to describe later extreme ice ages during the Cryogenian period.

There were four periods, each lasting about 10 million years, between 750 and 580 million years ago, when the earth is thought to have been covered with ice apart from the highest mountains, and average temperatures were about −50 °C (−58 °F). The snowball may have been partly due to the location of the supercontinent Rodinia straddling the Equator. Carbon dioxide combines with rain to weather rocks to form carbonic acid, which is then washed out to sea, thus extracting the greenhouse gas from the atmosphere. When the continents are near the poles, the advance of ice covers the rocks, slowing the reduction in carbon dioxide, but in the Cryogenian the weathering of Rodinia was able to continue unchecked until the ice advanced to the tropics. The process may have finally been reversed by the emission of carbon dioxide from volcanoes or the destabilization of methane gas hydrates. According to the alternative Slushball Earth theory, even at the height of the ice ages there was still open water at the Equator.

Emergence of eukaryotes

Modern taxonomy classifies life into three domains. The time of their origin is uncertain. The Bacteria domain probably first split off from the other forms of life (sometimes called Neomura), but this supposition is controversial. Soon after this, by 2 Ga, the Neomura split into the Archaea and the Eukarya. Eukaryotic cells (Eukarya) are larger and more complex than prokaryotic cells (Bacteria and Archaea), and the origin of that complexity is only now becoming known. The earliest fossils possessing features typical of fungi date to the Paleoproterozoic era, some 2.4 ago; these multicellular benthic organisms had filamentous structures capable of anastomosis.

Around this time, the first proto-mitochondrion was formed. A bacterial cell related to today's *Rickettsia*, which had evolved to metabolize oxygen, entered a larger prokaryotic cell, which lacked that capability. Perhaps the large cell attempted to digest the smaller one but failed (possibly due to the evolution of prey defenses). The smaller cell may have tried to parasitize the larger one. In any case, the smaller cell survived inside the larger cell. Using oxygen, it metabolized the larger cell's waste products and derived more energy. Part of this excess energy was returned to the host. The smaller cell replicated inside the larger one. Soon, a stable symbiosis developed between the large cell and the smaller cells inside it. Over time, the host cell acquired some genes from the smaller cells, and the two kinds became dependent on each other: the larger cell could not survive without the energy produced by the smaller ones, and these, in turn, could not survive without the raw materials provided by the larger cell. The whole cell is now considered a single organism, and the smaller cells are classified as organelles called mitochondria.

A similar event occurred with photosynthetic cyanobacteria entering large heterotrophic cells and becoming chloroplasts. Probably as a result of these changes, a line of cells capable of photosynthesis split off from the other eukaryotes more than 1 billion years ago. There were probably several such inclusion events. Besides the well-established endosymbiotic theory of the cellular origin of mitochondria and chloroplasts, there are theories that cells led to peroxisomes, spirochetes led to cilia and flagella, and that perhaps a DNA virus led to the cell nucleus, though none of them are widely accepted.

Archaeans, bacteria, and eukaryotes continued to diversify and to become more complex and better adapted to their environments. Each domain repeatedly split into multiple lineages, although little is known about the history of the archaea and bacteria. Around 1.1 Ga, the supercontinent Rodinia was assembling. The plant, animal, and fungi lines had split, though they still existed as solitary cells. Some of these lived in colonies, and gradually a division of labor began to take place; for instance, cells on the periphery might have started to assume different roles from those in the interior. Although the division between a colony with specialized cells and a multicellular organism is not always clear, around 1 billion years ago, the first multicellular plants emerged, probably green algae. Possibly by around 900 Ma true multicellularity had also evolved in animals.

At first, it probably resembled today's sponges, which have totipotent cells that allow a disrupted organism to reassemble itself. As the division of labor was completed in all lines of multicellular organisms, cells became more specialized and more dependent on each other; isolated cells would die.

Supercontinents in the Proterozoic

Reconstructions of tectonic plate movement in the past 250 million years (the Cenozoic and Mesozoic eras) can be made reliably using fitting of continental margins, ocean floor magnetic anomalies and paleomagnetic poles. No ocean crust dates back further than that, so earlier reconstructions are more difficult. Paleomagnetic poles are supplemented by geologic evidence such as orogenic belts, which mark the edges of ancient plates, and past distributions of flora and fauna.

The further back in time, the scarcer and harder to interpret the data get and the more uncertain the reconstructions.

Throughout the history of the Earth, there have been times when continents collided and formed a supercontinent, which later broke up into new continents. About 1000 to 830 Ma, most continental mass was united in the supercontinent Rodinia. Rodinia may have been preceded by Early-Middle Proterozoic continents called Nuna and Columbia.

After the break-up of Rodinia about 800 Ma, the continents may have formed another short-lived supercontinent around 550 Ma. The hypothetical supercontinent is sometimes referred to as Pannotia or Vendia. The evidence for it is a phase of continental collision known as the Pan-African orogeny, which joined the continental masses of current-day Africa, South America, Antarctica and Australia. The existence of Pannotia depends on the timing of the rifting between Gondwana (which included most of the landmass now in the Southern Hemisphere, as well as the Arabian Peninsula and the Indian subcontinent) and Laurentia (roughly equivalent to current-day North America). It is at least certain that by the end of the Proterozoic eon, most of the continental mass lay united in a position around the south pole.

Late Proterozoic climate and life

The end of the Proterozoic saw at least two Snowball Earths, so severe that the surface of the oceans may have been completely frozen. This happened about 716.5 and 635 Ma, in the Cryogenian period. The intensity and mechanism of both glaciations are still under investigation and harder to explain than the early Proterozoic Snowball Earth. Most paleoclimatologists think the cold episodes were linked to the formation of the supercontinent Rodinia. Because Rodinia was centered on the equator, rates of chemical weathering increased and carbon dioxide (CO_2) was taken from the atmosphere. Because CO_2 is an important greenhouse gas, climates cooled globally. In the same way, during the Snowball Earths most of the continental surface was covered with permafrost, which decreased chemical weathering again, leading to the end of the glaciations. An alternative hypothesis is that enough carbon dioxide escaped through volcanic outgassing that the resulting greenhouse effect raised global temperatures. Increased volcanic activity resulted from the break-up of Rodinia at about the same time.

The Cryogenian period was followed by the Ediacaran period, which was characterized by a rapid development of new multicellular lifeforms. Whether there is a connection between the end of the severe ice ages and the increase in diversity of life is not clear, but it does not seem coincidental. The new forms of life, called Ediacara biota, were larger and more diverse than ever. Though the taxonomy of most Ediacaran life forms is unclear, some were ancestors of groups of modern life. Important developments were the origin of muscular and neural cells. None of the Ediacaran fossils had hard body parts like skeletons. These first appear after the boundary between the Proterozoic and Phanerozoic eons or Ediacaran and Cambrian periods.

Phanerozoic Eon

The Phanerozoic is the current eon on Earth, which started approximately 542 million years ago. It consists of three eras: The Paleozoic, Mesozoic, and Cenozoic, and is the time when multi-cellular life greatly diversified into almost all the organisms known today.

The Paleozoic ("old life") era was the first and longest era of the Phanerozoic eon, lasting from 542 to 251 Ma. During the Paleozoic, many modern groups of life came into existence. Life colonized the land, first plants, then animals. Two major extinctions occurred. The continents formed at the break-up of Pannotia and Rodinia at the end of the Proterozoic slowly moved together again, forming the supercontinent Pangaea in the late Paleozoic.

The Mesozoic ("middle life") era lasted from 251 Ma to 66 Ma. It is subdivided into the Triassic, Jurassic, and Cretaceous periods. The era began with the Permian–Triassic extinction event, the most severe extinction event in the fossil record; 95% of the species on Earth died out. It ended with the Cretaceous–Paleogene extinction event that wiped out the dinosaurs..

The Cenozoic ("new life") era began at 66 Ma, and is subdivided into the Paleogene, Neogene, and Quaternary periods. These three periods are further split into seven subdivisions, with the Paleogene composed of The Paleocene, Eocene, and Oligocene, the Neogene divided into the Miocene, Pliocene, and the Quaternary composed of the Pleistocene, and Holocene.

Mammals, birds, amphibians, crocodilians, turtles, and lepidosaurs survived the Cretaceous–Paleogene extinction event that killed off the non-avian dinosaurs and many other forms of life, and this is the era during which they diversified into their modern forms.

Tectonics, paleogeography and climate

At the end of the Proterozoic, the supercontinent Pannotia had broken apart into the smaller continents Laurentia, Baltica, Siberia and Gondwana. During periods when continents move apart, more oceanic crust is formed by volcanic activity. Because young volcanic crust is relatively hotter and less dense than old oceanic crust, the ocean floors rise during such periods. This causes the sea level to rise. Therefore, in the first half of the Paleozoic, large areas of the continents were below sea level.

Early Paleozoic climates were warmer than today, but the end of the Ordovician saw a short ice age during which glaciers covered the south pole, where the huge continent Gondwana was situated. Traces of glaciation from this period are only found on former Gondwana. During the Late Ordovician ice age, a few mass extinctions took place, in which many brachiopods, trilobites, Bryozoa and corals disappeared. These marine species could probably not contend with the decreasing temperature of the sea water.

The continents Laurentia and Baltica collided between 450 and 400 Ma, during the Caledonian Orogeny, to form Laurussia (also known as Euramerica). Traces of the mountain belt this collision caused can be found in Scandinavia, Scotland, and the northern Appalachians. In the Devonian period (416–359 Ma) Gondwana and Siberia began to move towards Laurussia. The collision of Siberia with Laurussia caused the Uralian Orogeny, the collision of Gondwana with Laurussia is called the Variscan or Hercynian Orogeny in Europe or the Alleghenian Orogeny in North America. The latter phase took place during the Carboniferous period (359–299 Ma) and resulted in the formation of the last supercontinent, Pangaea.

By 180 Ma, Pangaea broke up into Laurasia and Gondwana.

Cambrian explosion

The rate of the evolution of life as recorded by fossils accelerated in the Cambrian period (542–488 Ma). The sudden emergence of many new species, phyla, and forms in this period is called the Cambrian Explosion. The biological fomenting in the Cambrian Explosion was unprecedented before and since that time. Whereas the Ediacaran life forms appear yet primitive and not easy to put in any modern group, at the end of the Cambrian most modern phyla were already present. The development of hard body parts such as shells, skeletons or exoskeletons in animals like molluscs, echinoderms, crinoids and arthropods (a well-known group of arthropods from the lower Paleozoic are the trilobites) made the preservation and fossilization of such life forms easier than those of their Proterozoic ancestors. For this reason, much more is known about life in and after the Cambrian than about that of older periods. Some of these Cambrian groups appear complex but are seemingly quite different from modern life; examples are *Anomalocaris* and *Haikouichthys*. More recently, however, these seem to have found a place in modern classification.

During the Cambrian, the first vertebrate animals, among them the first fishes, had appeared. A creature that could have been the ancestor of the fishes, or was probably closely related to it, was *Pikaia*. It had a primitive notochord, a structure that could have developed into a vertebral column later. The first fishes with jaws (Gnathostomata) appeared during the next geological period, the Ordovician. The colonisation of new niches resulted in massive body sizes. In this way, fishes with increasing sizes evolved during the early Paleozoic, such as the titanic placoderm *Dunkleosteus*, which could grow 7 meters (23 ft) long.

The diversity of life forms did not increase greatly because of a series of mass extinctions that define widespread biostratigraphic units called *biomeres*. After each extinction pulse, the continental shelf regions were repopulated by similar life forms that may have been evolving slowly elsewhere. By the late Cambrian, the trilobites had reached their greatest diversity and dominated nearly all fossil assemblages.

Colonization of land

Oxygen accumulation from photosynthesis resulted in the formation of an ozone layer that absorbed much of the Sun's ultraviolet radiation, meaning unicellular organisms that reached land were less likely to die, and prokaryotes began to multiply and become better adapted to survival out of the water. Prokaryote lineages had probably colonized the land as early as 2.6 Ga even before the origin of the eukaryotes. For a long time, the land remained barren of multicellular organisms. The supercontinent Pannotia formed around 600 Ma and then broke apart a short 50 million years later. Fish, the earliest vertebrates, evolved in the oceans around 530 Ma. A major extinction event occurred near the end of the Cambrian period, which ended 488 Ma.

Several hundred million years ago, plants (probably resembling algae) and fungi started growing at the edges of the water, and then out of it. The oldest fossils of land fungi and plants date to 480–460 Ma, though molecular evidence suggests the fungi may have colonized the land as early as 1000 Ma and the plants 700 Ma. Initially remaining close to the water's edge, mutations and variations resulted in further colonization of this new environment. The timing of the first animals to leave the oceans is not precisely known: the oldest clear evidence is of arthropods on land around 450 Ma, perhaps thriving and becoming better adapted due to the vast food source provided by the terrestrial plants. There is also unconfirmed evidence that arthropods may have appeared on land as early as 530 Ma.

Evolution of tetrapods

At the end of the Ordovician period, 443 Ma, additional extinction events occurred, perhaps due to a concurrent ice age. Around 380 to 375 Ma, the first tetrapods evolved from fish. Fins evolved to become limbs that the first tetrapods used to lift their heads out of the water to breathe air. This would let them live in oxygen-poor water, or pursue small prey in shallow water. They may have later ventured on land for brief periods. Eventually, some of them became so well adapted to terrestrial life that they spent their adult lives on land, although they hatched in the water and returned to lay their eggs. This was the origin of the amphibians. About 365 Ma, another period of extinction occurred, perhaps as a result of global cooling. Plants evolved seeds, which dramatically accelerated their spread on land, around this time (by approximately 360 Ma).

About 20 million years later (340 Ma), the amniotic egg evolved, which could be laid on land, giving a survival advantage to tetrapod embryos. This resulted in the divergence of amniotes from amphibians. Another 30 million years (310 Ma) saw the divergence of the synapsids (including mammals) from the sauropsids (including birds and reptiles). Other groups of organisms continued to evolve, and lines diverged—in fish, insects, bacteria, and so on—but less is known of the details.

After yet another, the most severe extinction of the period (251~250 Ma), around 230 Ma, dinosaurs split off from their reptilian ancestors. The Triassic–Jurassic extinction event at 200 Ma spared many of the dinosaurs, and they soon became dominant among the vertebrates. Though some mammalian lines began to separate during this period, existing mammals were probably small animals resembling shrews.

The boundary between avian and non-avian dinosaurs is not clear, but *Archaeopteryx*, traditionally considered one of the first birds, lived around 150 Ma.

The earliest evidence for the angiosperms evolving flowers is during the Cretaceous period, some 20 million years later (132 Ma).

Extinctions

The first of five great mass extinctions was the Ordovician-Silurian extinction. Its possible cause was the intense glaciation of Gondwana, which eventually led to a snowball earth. 60% of marine invertebrates became extinct and 25% of all families.

The second mass extinction was the Late Devonian extinction, probably caused by the evolution of trees, which could have led to the depletion of greenhouse gases (like CO2) or the eutrophication of water. 70% of all species became extinct.

The third mass extinction was the Permian-Triassic, or the Great Dying, event was possibly caused by some combination of the Siberian Traps volcanic event, an asteroid impact, methane hydrate gasification, sea level fluctuations, and a major anoxic event. Either the proposed Wilkes Land crater in Antarctica or Bedout structure off the northwest coast of Australia may indicate an impact connection with the Permian-Triassic extinction. But it remains uncertain whether either these or other proposed Permian-Triassic boundary craters are either real impact craters or even contemporaneous with the Permian-Triassic extinction event. This was by far the deadliest extinction ever, with about 57% of all families and 83% of all genera killed.

The fourth mass extinction was the Triassic-Jurassic extinction event in which almost all synapsids and archosaurs became extinct, probably due to new competition from dinosaurs.

The fifth and most recent mass extinction was the K-T extinction. In 66 Ma, a 10-kilometer (6.2 mi) asteroid struck Earth just off the Yucatán Peninsula—somewhere in the southwestern tip of then Laurasia—where the Chicxulub crater is today. This ejected vast quantities of particulate matter and vapor into the air that occluded sunlight, inhibiting photosynthesis. 75% of all life, including the non-avian dinosaurs, became extinct, marking the end of the Cretaceous period and Mesozoic era.

Diversification of mammals

The first true mammals evolved in the shadows of dinosaurs and other large archosaurs that filled the world by the late Triassic. The first mammals were very small, and were probably nocturnal to escape predation. Mammal diversification truly began only after the Cretaceous-Paleogene extinction event. By the early Paleocene the earth recovered from the extinction, and mammalian diversity increased. Creatures like *Ambulocetus* took to the oceans to eventually evolve into whales, whereas some creatures, like primates, took to the trees. This all changed during the mid to late Eocene when the circum-Antarctic current formed between Antarctica and Australia which disrupted weather patterns on a global scale. Grassless savanna began to predominate much of the landscape, and mammals such as *Andrewsarchus* rose up to become the largest known terrestrial predatory mammal ever, and early whales like *Basilosaurus* took control of the seas.

The evolution of grass brought a remarkable change to the Earth's landscape, and the new open spaces created pushed mammals to get bigger and bigger. Grass started to expand in the Miocene, and the Miocene is where many modern- day mammals first appeared. Giant ungulates like *Paraceratherium* and *Deinotherium* evolved to rule the grasslands. The evolution of grass also brought primates down from the trees, and started human evolution. The first big cats evolved during this time as well. The Tethys Sea was closed off by the collision of Africa and Europe.

The formation of Panama was perhaps the most important geological event to occur in the last 60 million years. Atlantic and Pacific currents were closed off from each other, which caused the formation of the Gulf Stream, which made Europe warmer. The land bridge allowed the isolated creatures of South America to migrate over to North America, and vice versa. Various species migrated south, leading to the presence in South America of llamas, the spectacled bear, kinkajous and jaguars.

Three million years ago saw the start of the Pleistocene epoch, which featured dramatic climactic changes due to the ice ages. The ice ages led to the evolution of modern man in Saharan Africa and expansion. The mega-fauna that dominated fed on grasslands that, by now, had taken over much of the subtropical world. The large amounts of water held in the ice allowed for various bodies of water to shrink and sometimes disappear such as the North Sea and the Bering Strait. It is believed by many that a huge migration took place along Beringia which is why, today, there are camels (which evolved and became extinct in North America), horses (which evolved and became extinct in North America), and Native Americans. The ending of the last ice age coincided with the expansion of man, along with a massive die out of ice age mega-fauna. This extinction is nicknamed "the Sixth Extinction".

Human evolution

A small African ape living around 6 Ma was the last animal whose descendants would include both modern humans and their closest relatives, the chimpanzees. Only two branches of its family tree have surviving descendants. Very soon after the split, for reasons that are still unclear, apes in one branch developed the ability to walk upright. Brain size increased rapidly, and by 2 Ma, the first animals classified in the genus *Homo* had appeared. Of course, the line between different species or even genera is somewhat arbitrary as organisms continuously change over generations. Around the same time, the other branch split into the ancestors of the common chimpanzee and the ancestors of the bonobo as evolution continued simultaneously in all life forms.

The ability to control fire probably began in *Homo erectus* (or *Homo ergaster*), probably at least 790,000 years ago but perhaps as early as 1.5 Ma. The use and discovery of controlled fire may even predate *Homo erectus*. Fire was possibly used by the early Lower Paleolithic (Oldowan) hominid *Homo habilis* or strong australopithecines such as *Paranthropus*.

It is more difficult to establish the origin of language; it is unclear whether *Homo erectus* could speak or if that capability had not begun until *Homo sapiens*. As brain size increased, babies were born earlier, before their heads grew too large to pass through the pelvis. As a result, they exhibited more plasticity, and thus possessed an increased capacity to learn and required a longer period of dependence. Social skills became more complex, language became more sophisticated, and tools became more elaborate. This contributed to further cooperation and intellectual development. Modern humans (*Homo sapiens*) are believed to have originated around 200,000 years ago or earlier in Africa; the oldest fossils date back to around 160,000 years ago. The first humans to show signs of spirituality are the Neanderthals (usually classified as a separate species with no surviving descendants); they buried their dead, often with no sign of food or tools. However, evidence of more sophisticated beliefs, such as the early Cro-Magnon cave paintings (probably with magical or religious significance) did not appear until 32,000 years ago. Cro-Magnons also left behind stone figurines such as Venus of Willendorf, probably also signifying religious belief. By 11,000 years ago, *Homo sapiens* had reached the southern tip of South America, the last of the uninhabited continents (except for Antarctica, which remained undiscovered until 1820 AD). Tool use and communication continued to improve, and interpersonal relationships became more intricate.

Human history

Throughout more than 90% of its history, *Homo sapiens* lived in small bands as nomadic hunter-gatherers. As language became more complex, the ability to remember and communicate information resulted, according to a theory proposed by Richard Dawkins, in a new replicator: the meme. Ideas could be exchanged quickly and passed down the generations. Cultural evolution quickly outpaced biological evolution, and history proper began. Between 8500 and 7000 BC, humans in the Fertile Crescent in the Middle East began the systematic husbandry of plants and animals: agriculture. This spread to neighboring regions, and developed independently elsewhere, until most *Homo sapiens* lived sedentary lives in permanent settlements as farmers. Not all societies abandoned nomadism, especially those in isolated areas of the globe poor in domesticable plant species, such as Australia. However, among those civilizations that did adopt agriculture, the relative stability and increased productivity provided by farming allowed the population to expand.

Agriculture had a major impact; humans began to affect the environment as never before. Surplus food allowed a priestly or governing class to arise, followed by increasing division of labor. This led to Earth's first civilization at Sumer in the Middle East, between 4000 and 3000 BC. Additional civilizations quickly arose in ancient Egypt, at the Indus River valley and in China. The invention of writing enabled complex societies to arise: record-keeping and libraries served as a storehouse of knowledge and increased the cultural transmission of information. Humans no longer had to spend all their time working for survival, enabling the first specialized occupations (e.g. craftsmen, merchants, priests, etc.). Curiosity and education drove the pursuit of knowledge and wisdom, and various disciplines, including science (in a primitive form), arose. This in turn led to the emergence of increasingly larger and more complex civilizations, such as the first empires, which at times traded with one another, or fought for territory and resources.

By around 500 BC, there were advanced civilizations in the Middle East, Iran, India, China, and Greece, at times expanding, at times entering into decline. In 221 BC, China became a single polity that would grow to spread its culture throughout East Asia, and it has remained the most populous nation in the world. During this period, famous Hindu texts known as vedas came in existence in Indus valley civilization. This civilization developed in warfare, arts, science, mathematics and in architect. The fundamentals of Western civilization were largely shaped in Ancient Greece, with the world's first democratic government and major advances in philosophy, science. Ancient Rome in law, government, and engineering. The Roman Empire was Christianized by Emperor Constantine in the early 4th century and declined by the end of the 5th. Beginning with the 7th century, Christianization of Europe began. In 610, Islam was founded and quickly became the dominant religion in Western Asia. The House of Wisdom was established in Abbasid-era Baghdad, Iraq. It is considered to have been a major intellectual center during the Islamic Golden Age, where Muslim scholars in Baghdad and Cairo flourished from the ninth to the thirteenth centuries until the Mongol sack of Baghdad in 1258 AD. In 1054 AD the Great Schism between the Roman Catholic Church and the Eastern Orthodox Church led to the prominent cultural differences between Western and Eastern Europe.

In the 14th century, the Renaissance began in Italy with advances in religion, art, and science. At that time the

Christian Church as a political entity lost much of its power. In 1492, Christopher Columbus reached the Americas, initiating great changes to the new world. European civilization began to change beginning in 1500, leading to the scientific and industrial revolutions. That continent began to exert political and cultural dominance over human societies around the world, a time known as the Colonial era (also see Age of Discovery). In the 18th century a cultural movement known as the Age of Enlightenment further shaped the mentality of Europe and contributed to its secularization. From 1914 to 1918 and 1939 to 1945, nations around the world were embroiled in world wars. Established following World War I, the League of Nations was a first step in establishing international institutions to settle disputes peacefully. After failing to prevent World War II, mankind's bloodiest conflict, it was replaced by the United Nations. After the war, many new states were formed, declaring or being granted independence in a period of decolonization. The democratic capitalist United States and the socialist Soviet Union became the world's dominant superpowers for a time, and they held an ideological, often-violent rivalry known as the Cold War until the dissolution of the latter. In 1992, several European nations joined in the European Union. As transportation and communication improved, the economies and political affairs of nations around the world have become increasingly intertwined. This globalization has often produced both conflict and cooperation.

Recent events

Change has continued at a rapid pace from the mid-1940s to today. Technological developments include nuclear weapons, computers, genetic engineering, and nanotechnology. Economic globalization, spurred by advances in communication and transportation technology, has influenced everyday life in many parts of the world. Cultural and institutional forms such as democracy, capitalism, and environmentalism have increased influence. Major concerns and problems such as disease, war, poverty, violent radicalism, and recently, human-caused climate change have risen as the world population increases.

In 1957, the Soviet Union launched the first artificial satellite into orbit and, soon afterward, Yuri Gagarin became the first human in space. Neil Armstrong, an American, was the first to set foot on another astronomical object, the Moon. Unmanned probes have been sent to all the known planets in the Solar System, with some (such as the two Voyager spacecraft) having left the Solar System. Five space agencies, representing over fifteen countries, have worked together to build the International Space Station. Aboard it, there has been a continuous human presence in space since 2000. The World Wide Web became a part of everyday life in the 1990s, and since then has become an indispensable source of information in the developed world.

Chapter 19

History of Astronomy

Astronomy is the oldest of the natural sciences, dating back to antiquity, with its origins in the religious, mythological, cosmological, calendrical, and astrological beliefs and practices of prehistory: vestiges of these are still found in astrology, a discipline long interwoven with public and governmental astronomy. It was not completely separated in Europe (see astrology and astronomy) during the Copernican Revolution starting in 1543. In some cultures, astronomical data was used for astrological prognostication. The study of astronomy has received financial and social support from many institutions, especially the Church, which was its largest source of support between the 12th century to the Enlightenment.

Ancient astronomers were able to differentiate between stars and planets, as stars remain relatively fixed over the centuries while planets will move an appreciable amount during a comparatively short time.

Early history

Early cultures identified celestial objects with gods and spirits. They related these objects (and their movements) to phenomena such as rain, drought, seasons, and tides. It is generally believed that the first astronomers were priests, and that they understood celestial objects and events to be manifestations of the divine, hence early astronomy's connection to what is now called astrology. A 32,500 year old carved ivory Mammoth tusk could contain the oldest known star chart (resembling the constellation Orion). It has also been suggested that drawing on the wall of the Lascaux caves in France dating from 33,000 to 10,000 years ago could be a graphical representation of the Pleiades, the Summer Triangle, and the Northern Crown. Ancient structures with possibly astronomical alignments (such as Stonehenge) probably fulfilled astronomical, religious, and social functions.

Calendars of the world have often been set by observations of the Sun and Moon (marking the day, month and year), and were important to agricultural societies, in which the harvest depended on planting at the correct time of year, and for which the nearly full moon was the only lighting for night-time travel into city markets. The common modern calendar is based on the Roman calendar. Although originally a lunar calendar, it broke the traditional link of the month to the phases of the Moon and divided the year into twelve almost-equal months, that mostly alternated between thirty and thirty-one days. Julius Caesar instigated calendar reform in 46 BCE and introduced what is now called the Julian calendar, based upon the 365 1⁄4 day year length originally proposed by the 4th century BCE Greek astronomer Callippus.

Ancient times

Mesopotamia

The origins of Western astronomy can be found in Mesopotamia, the "land between the rivers" Tigris and

Euphrates, where the ancient kingdoms of Sumer, Assyria, and Babylonia were located. A form of writing known as cuneiform emerged among the Sumerians around 3500–3000 BC. Our knowledge of Sumerian astronomy is indirect, via the earliest Babylonian star catalogues dating from about 1200 BC. The fact that many star names appear in Sumerian suggests a continuity reaching into the Early Bronze Age. Astral theology, which gave planetary gods an important role in Mesopotamian mythology and religion, began with the Sumerians. They also used a sexagesimal (base 60) place-value number system, which simplified the task of recording very large and very small numbers. The modern practice of dividing a circle into 360 degrees, or an hour into 60 minutes, began with the Sumerians. For more information, see the articles on Babylonian numerals and mathematics.

Classical sources frequently use the term Chaldeans for the astronomers of Mesopotamia, who were, in reality, priest-scribes specializing in astrology and other forms of divination.

The first evidence of recognition that astronomical phenomena are periodic and of the application of mathematics to their prediction is Babylonian. Tablets dating back to the Old Babylonian period document the application of mathematics to the variation in the length of daylight over a solar year. Centuries of Babylonian observations of celestial phenomena are recorded in the series of cuneiform tablets known as the *Enūma Anu Enlil*. The oldest significant astronomical text that we possess is Tablet 63 of the *Enūma Anu Enlil*, the Venus tablet of Ammi-saduqa, which lists the first and last visible risings of Venus over a period of about 21 years and is the earliest evidence that the phenomena of a planet were recognized as periodic. The MUL.APIN, contains catalogues of stars and constellations as well as schemes for predicting heliacal risings and the settings of the planets, lengths of daylight measured by a water clock, gnomon, shadows, and intercalations. The Babylonian GU text arranges stars in 'strings' that lie along declination circles and thus measure right-ascensions or time-intervals, and also employs the stars of the zenith, which are also separated by given right-ascensional differences.

A significant increase in the quality and frequency of Babylonian observations appeared during the reign of Nabonassar (747–733 BC). The systematic records of ominous phenomena in Babylonian astronomical diaries that began at this time allowed for the discovery of a repeating 18-year cycle of lunar eclipses, for example. The Greek astronomer Ptolemy later used Nabonassar's reign to fix the beginning of an era, since he felt that the earliest usable observations began at this time.

The last stages in the development of Babylonian astronomy took place during the time of the Seleucid Empire (323–60 BC). In the 3rd century BC, astronomers began to use "goal-year texts" to predict the motions of the planets. These texts compiled records of past observations to find repeating occurrences of ominous phenomena for each planet. About the same time, or shortly afterwards, astronomers created mathematical models that allowed them to predict these phenomena directly, without consulting past records. A notable Babylonian astronomer from this time was Seleucus of Seleucia, who was a supporter of the heliocentric model.

Babylonian astronomy was the basis for much of what was done in Greek and Hellenistic astronomy, in classical Indian astronomy, in Sassanian Iran, in Byzantium, in Syria, in Islamic astronomy, in Central Asia, and in Western Europe.

India

Astronomy in the Indian subcontinent dates back to the period of Indus Valley Civilization during 3rd millennium BCE, when it was used to create calendars. As the Indus Valley civilization did not leave behind written documents, the oldest extant Indian astronomical text is the Vedanga Jyotisha, dating from the Vedic period. Vedanga Jyotisha describes rules for tracking the motions of the Sun and the Moon for the purposes of ritual. During the 6th century, astronomy was influenced by the Greek and Byzantine astronomical traditions.

Aryabhata (476–550), in his magnum opus *Aryabhatiya* (499), propounded a computational system based on a planetary model in which the Earth was taken to be spinning on its axis and the periods of the planets were given with respect to the Sun. He accurately calculated many astronomical constants, such as the periods of the planets, times of the solar and lunar eclipses, and the instantaneous motion of the Moon. Early followers of Aryabhata's model included Varahamihira, Brahmagupta, and Bhaskara II.

Astronomy was advanced during the Shunga Empire and many star catalogues were produced during this time. The Shunga period is known as the "Golden age of astronomy in India". It saw the development of calculations for the motions and places of various planets, their rising and setting, conjunctions, and the calculation of eclipses.

Indian astronomers by the 6th century believed that comets were celestial bodies that re-appeared periodically. This was the view expressed in the 6th century by the astronomers Varahamihira and Bhadrabahu, and the 10th-century astronomer Bhattotpala listed the names and estimated periods of certain comets, but it is unfortunately not known how these figures were calculated or how accurate they were.

Bhāskara II (1114–1185) was the head of the astronomical observatory at Ujjain, continuing the mathematical tradition of Brahmagupta. He wrote the *Siddhantasiromani* which consists of two parts: *Goladhyaya* (sphere) and *Grahaganita* (mathematics of the planets). He also calculated the time taken for the Earth to orbit the Sun to 9 decimal places. The Buddhist University of Nalanda at the time offered formal courses in astronomical studies.

Other important astronomers from India include Madhava of Sangamagrama, Nilakantha Somayaji and Jyeshtadeva, who were members of the Kerala school of astronomy and mathematics from the 14th century to the 16th century. Nilakantha Somayaji, in his *Aryabhatiyabhasya*, a commentary on Aryabhata's *Aryabhatiya*, developed his own computational system for a partially heliocentric planetary model, in which Mercury, Venus, Mars, Jupiter and Saturn orbit the Sun, which in turn orbits the Earth, similar to the Tychonic system later proposed by Tycho Brahe in the late 16th century. Nilakantha's system, however, was mathematically more efficient than the Tychonic system, due to correctly taking into account the equation of the centre and latitudinal motion of Mercury and Venus. Most astronomers of the Kerala school of astronomy and mathematics who followed him accepted his planetary model.

Greece and Hellenistic world

The Ancient Greeks developed astronomy, which they treated as a branch of mathematics, to a highly sophisticated level. The first geometrical, three-dimensional models to explain the apparent motion of the planets were developed in the 4th century BC by Eudoxus of Cnidus and Callippus of Cyzicus. Their models were based on nested homocentric spheres centered upon the Earth. Their younger contemporary Heraclides Ponticus proposed that the Earth rotates around its axis.

A different approach to celestial phenomena was taken by natural philosophers such as Plato and Aristotle. They were less concerned with developing mathematical predictive models than with developing an explanation of the reasons for the motions of the Cosmos. In his *Timaeus*, Plato described the universe as a spherical body divided into circles carrying the planets and governed according to harmonic intervals by a world soul. Aristotle, drawing on the mathematical model of Eudoxus, proposed that the universe was made of a complex system of concentric spheres, whose circular motions combined to carry the planets around the earth. This basic cosmological model prevailed, in various forms, until the 16th century.

In the 3rd century BC Aristarchus of Samos was the first to suggest a heliocentric system, although only fragmentary descriptions of his idea survive. Eratosthenes estimated the circumference of the Earth with great accuracy.

Greek geometrical astronomy developed away from the model of concentric spheres to employ more complex models in which an eccentric circle would carry around a smaller circle, called an epicycle which in turn carried around a planet. The first such model is attributed to Apollonius of Perga and further developments in it were carried out in the 2nd century BC by Hipparchus of Nicea. Hipparchus made a number of other contributions, including the first measurement of precession and the compilation of the first star catalog in which he proposed our modern system of apparent magnitudes.

The Antikythera mechanism, an ancient Greek astronomical observational device for calculating the movements of the Sun and the Moon, possibly the planets, dates from about 150–100 BC, and was the first ancestor of an astronomical computer. It was discovered in an ancient shipwreck off the Greek island of Antikythera, between Kythera and Crete. The device became famous for its use of a differential gear, previously believed to have been invented in the 16th century, and the miniaturization and complexity of its parts, comparable to a clock made in the 18th century. The original mechanism is displayed in the Bronze collection of the National Archaeological Museum of Athens, accompanied by a replica.

Depending on the historian's viewpoint, the acme or corruption of physical Greek astronomy is seen with Ptolemy of Alexandria, who wrote the classic comprehensive presentation of geocentric astronomy, the *Megale Syntaxis* (Great Synthesis), better known by its Arabic title *Almagest*, which had a lasting effect on astronomy up to the Renaissance. In his *Planetary Hypotheses*, Ptolemy ventured into the realm of cosmology, developing a physical model of his geometric system, in a universe many times smaller than the more realistic conception of Aristarchus of Samos four centuries earlier.

Egypt

The precise orientation of the Egyptian pyramids affords a lasting demonstration of the high degree of technical skill in watching the heavens attained in the 3rd millennium BC. It has been shown the Pyramids were aligned towards the pole star, which, because of the precession of the equinoxes, was at that time Thuban, a faint star in the constellation of Draco. Evaluation of the site of the temple of Amun-Re at Karnak, taking into account the change over time of the obliquity of the ecliptic, has shown that the Great Temple was aligned on the rising of the midwinter Sun. The length of the corridor down which sunlight would travel would have limited illumination at other times of the year. The Egyptians also found the position of Sirius (the dog star) who they believed was Anubis their Jackal headed god moving through the heavens. Its position was critical to their civilisation as when it rose heliacal in the east before sunrise it foretold the flooding of the Nile. It is also where we get the phrase 'dog days of summer' from.

Astronomy played a considerable part in religious matters for fixing the dates of festivals and determining the hours of the night. The titles of several temple books are preserved recording the movements and phases of the sun, moon and stars. The rising of Sirius (Egyptian: Sopdet, Greek: Sothis) at the beginning of the inundation was a particularly important point to fix in the yearly calendar.

Writing in the Roman era, Clement of Alexandria gives some idea of the importance of astronomical observations to the sacred rites:

And after the Singer advances the Astrologer (ὡροσκόπος), with a *horologium* (ὡρολόγιον) in his hand, and a *palm* (φοίνιξ), the symbols of astrology. He must know by heart the Hermetic astrological books, which are four in number. Of these, one is about the arrangement of the fixed stars that are visible; one on the positions of the Sun and Moon and five planets; one on the conjunctions and phases of the Sun and Moon; and one concerns their risings.

The Astrologer's instruments (*horologium* and *palm*) are a plumb line and sighting instrument. They have been identified with two inscribed objects in the Berlin Museum; a short handle from which a plumb line was hung, and a palm branch with a sight-slit in the broader end. The latter was held close to the eye, the former in the other hand, perhaps at arm's length. The "Hermetic" books which Clement refers to are the Egyptian theological texts, which probably have nothing to do with Hellenistic Hermetism.

From the tables of stars on the ceiling of the tombs of Rameses VI and Rameses IX it seems that for fixing the hours of the night a man seated on the ground faced the Astrologer in such a position that the line of observation of the pole star passed over the middle of his head. On the different days of the year each hour was determined by a fixed star culminating or nearly culminating in it, and the position of these stars at the time is given in the tables as in the centre, on the left eye, on the right shoulder, etc. According to the texts, in founding or rebuilding temples the north axis was determined by the same apparatus, and we may conclude that it was the usual one for astronomical observations. In careful hands it might give results of a high degree of accuracy.

China

The astronomy of East Asia began in China. Solar term was completed in Warring States period. The knowledge of Chinese astronomy was introduced into East Asia.

Astronomy in China has a long history. Detailed records of astronomical observations were kept from about the 6th century BC, until the introduction of Western astronomy and the telescope in the 17th century. Chinese astronomers were able to precisely predict eclipses.

Much of early Chinese astronomy was for the purpose of timekeeping. The Chinese used a lunisolar calendar, but because the cycles of the Sun and the Moon are different, astronomers often prepared new calendars and made observations for that purpose.

Astrological divination was also an important part of astronomy. Astronomers took careful note of "guest stars"(Chinese: pinyin: *kèxīng*; lit.: 'guest star') which suddenly appeared among the fixed stars. They were the first to record a supernova, in the Astrological Annals of the Houhanshu in 185 AD. Also, the supernova that created the Crab Nebula in 1054 is an example of a "guest star" observed by Chinese astronomers, although it was not recorded by their European contemporaries. Ancient astronomical records of phenomena like supernovae and comets are sometimes used in modern astronomical studies.

The world's first star catalogue was made by Gan De, a Chinese astronomer, in the 4th century BC.

Mesoamerica

Maya astronomical codices include detailed tables for calculating phases of the Moon, the recurrence of eclipses, and the appearance and disappearance of Venus as morning and evening star. The Maya based their calendrics in the carefully calculated cycles of the Pleiades, the Sun, the Moon, Venus, Jupiter, Saturn, Mars, and also they had a precise description of the eclipses as depicted in the Dresden Codex, as well as the ecliptic or zodiac, and the Milky Way was crucial in their Cosmology. A number of important Maya structures are believed to have been oriented toward the extreme risings and settings of Venus. To the ancient Maya, Venus was the patron of war and many recorded battles are believed to have been timed to the motions of this planet. Mars is also mentioned in preserved astronomical codices and early mythology.

Although the Maya calendar was not tied to the Sun, John Teeple has proposed that the Maya calculated the solar year to somewhat greater accuracy than the Gregorian calendar. Both astronomy and an intricate numerological scheme for the measurement of time were vitally important components of Maya religion.

Prehistoric Europe

Since 1990 our understanding of prehistoric Europeans has been radically changed by discoveries of ancient astronomical artifacts throughout Europe. The artifacts demonstrate that Neolithic and Bronze Age Europeans had a sophisticated knowledge of mathematics and astronomy.

Among the discoveries are:

- Paleolithic archaeologist Alexander Marshack put forward a theory in 1972 that bone sticks from locations like Africa and Europe from possibly as long ago as 35,000 BCE could be marked in ways that tracked the Moon's phases, an interpretation that has met with criticism.
- The Warren Field calendar in the Dee River valley of Scotland's Aberdeenshire. First excavated in 2004 but only in 2013 revealed as a find of huge significance, it is to date the world's oldest known calendar, created around 8000 BC and predating all other calendars by some 5,000 years. The calendar takes the form of an early Mesolithic monument containing a series of 12 pits which appear to help the observer track lunar months by mimicking the phases of the Moon. It also aligns to sunrise at the winter solstice, thus coordinating the solar year with the lunar cycles. The monument had been maintained and periodically reshaped, perhaps up to hundreds of times, in response to shifting solar/lunar cycles, over the course of 6,000 years,

until the calendar fell out of use around 4,000 years ago.

- Goseck circle is located in Germany and belongs to the linear pottery culture. First discovered in 1991, its significance was only clear after results from archaeological digs became available in 2004. The site is one of hundreds of similar circular enclosures built in a region encompassing Austria, Germany, and the Czech Republic during a 200-year period starting shortly after 5000 BC.
- The Nebra sky disc is a Bronze Age bronze disc that was buried in Germany, not far from the Goseck circle, around 1600 BC. It measures about 30 cm diameter with a mass of 2.2 kg and displays a blue-green patina (from oxidization) inlaid with gold symbols. Found by archeological thieves in 1999 and recovered in Switzerland in 2002, it was soon recognized as a spectacular discovery, among the most important of the 20th century. Investigations revealed that the object had been in use around 400 years before burial (2000 BC), but that its use had been forgotten by the time of burial. The inlaid gold depicted the full moon, a crescent moon about 4 or 5 days old, and the Pleiades star cluster in a specific arrangement forming the earliest known depiction of celestial phenomena. Twelve lunar months pass in 354 days, requiring a calendar to insert a leap month every two or three years in order to keep synchronized with the solar year's seasons (making it lunisolar). The earliest known descriptions of this coordination were recorded by the Babylonians in 6th or 7th centuries BC, over one thousand years

later. Those descriptions verified ancient knowledge of the Nebra sky disc's celestial depiction as the precise arrangement needed to judge when to insert the intercalary month into a lunisolar calendar, making it an astronomical clock for regulating such a calendar a thousand or more years before any other known method.

- The Kokino site, discovered in 2001, sits atop an extinct volcanic cone at an elevation of 1,013 metres (3,323 ft), occupying about 0.5 hectares overlooking the surrounding countryside in North Macedonia. A Bronze Age astronomical observatory was constructed there around 1900 BC and continuously served the nearby community that lived there until about 700 BC. The central space was used to observe the rising of the Sun and full moon. Three markings locate sunrise at the summer and winter solstices and at the two equinoxes. Four more give the minimum and maximum declinations of the full moon: in summer, and in winter. Two measure the lengths of lunar months. Together, they reconcile solar and lunar cycles in marking the 235 lunations that occur during 19 solar years, regulating a lunar calendar. On a platform separate from the central space, at lower elevation, four stone seats (thrones) were made in north-south alignment, together with a trench marker cut in the eastern wall. This marker allows the rising Sun's light to fall on only the second throne, at midsummer (about July 31). It was used for ritual ceremony linking the ruler to the local sun god, and also marked the end of the growing season and time for harvest.

- Golden hats of Germany, France and Switzerland dating from 1400–800 BC are associated with the Bronze Age Urnfield culture. The Golden hats are decorated with a spiral motif of the Sun and the Moon. They were probably a kind of calendar used to calibrate between the lunar and solar calendars. Modern scholarship has demonstrated that the ornamentation of the gold leaf cones of the Schifferstadt type, to which the Berlin Gold Hat example belongs, represent systematic sequences in terms of number and types of ornaments per band. A detailed study of the Berlin example, which is the only fully preserved one, showed that the symbols probably represent a lunisolar calendar. The object would have permitted the determination of dates or periods in both lunar and solar calendars.

Medieval Middle East

The Arabic and the Persian world under Islam had become highly cultured, and many important works of knowledge from Greek astronomy and Indian astronomy and Persian astronomy were translated into Arabic, used and stored in libraries throughout the area. An important contribution by Islamic astronomers was their emphasis on observational astronomy. This led to the emergence of the first astronomical observatories in the Muslim world by the early 9th century. Zij star catalogues were produced at these observatories.

In the 10th century, Abd al-Rahman al-Sufi (Azophi) carried out observations on the stars and described their positions, magnitudes, brightness, and colour and drawings for each constellation in his *Book of Fixed Stars*. He also gave the first descriptions and pictures of "A Little Cloud" now known as the Andromeda Galaxy. He mentions it as lying before the mouth of a Big Fish, an Arabic constellation. This "cloud" was apparently commonly known to the Isfahan astronomers, very probably before 905 AD. The first recorded mention of the Large Magellanic Cloud was also given by al-Sufi. In 1006, Ali ibn Ridwan observed SN 1006, the brightest supernova in recorded history, and left a detailed description of the temporary star.

In the late 10th century, a huge observatory was built near Tehran, Iran, by the astronomer Abu-Mahmud al-Khujandi who observed a series of meridian transits of the Sun, which allowed him to calculate the tilt of the Earth's axis relative to the Sun. He noted that measurements by earlier (Indian, then Greek) astronomers had found higher values for this angle, possible evidence that the axial tilt is not constant but was in fact decreasing. In 11th-century Persia, Omar Khayyám compiled many tables and performed a reformation of the calendar that was more accurate than the Julian and came close to the Gregorian.

Other Muslim advances in astronomy included the collection and correction of previous astronomical data, resolving significant problems in the Ptolemaic model, the development of the universal latitude-independent astrolabe by Arzachel, the invention of numerous other astronomical instruments, Ja'far Muhammad ibn Mūsā ibn Shākir's belief that the heavenly bodies and celestial spheres were subject to the same physical laws as Earth, the first elaborate experiments related to astronomical phenomena, the introduction of exacting empirical observations and experimental techniques, and the introduction of empirical testing by Ibn al-Shatir, who produced the first model of lunar motion which matched physical observations.

Natural philosophy (particularly Aristotelian physics) was separated from astronomy by Ibn al-Haytham (Alhazen) in the 11th century, by Ibn al-Shatir in the 14th century, and Qushji in the 15th century, leading to the development of an astronomical physics.

Medieval Western Europe

After the significant contributions of Greek scholars to the development of astronomy, it entered a relatively static era in Western Europe from the Roman era through the 12th century. This lack of progress has led some astronomers to assert that nothing happened in Western European astronomy during the Middle Ages. Recent investigations, however, have revealed a more complex picture of the study and teaching of astronomy in the period from the 4th to the 16th centuries.

Western Europe entered the Middle Ages with great difficulties that affected the continent's intellectual production. The advanced astronomical treatises of classical antiquity were written in Greek, and with the decline of knowledge of that language, only simplified summaries and practical texts were available for study. The most influential writers to pass on this ancient tradition in Latin were Macrobius, Pliny, Martianus Capella, and Calcidius. In the 6th century Bishop Gregory of

Tours noted that he had learned his astronomy from reading Martianus Capella, and went on to employ this rudimentary astronomy to describe a method by which monks could determine the time of prayer at night by watching the stars.

In the 7th century the English monk Bede of Jarrow published an influential text, *On the Reckoning of Time*, providing churchmen with the practical astronomical knowledge needed to compute the proper date of Easter using a procedure called the *computus*. This text remained an important element of the education of clergy from the 7th century until well after the rise of the Universities in the 12th century.

The range of surviving ancient Roman writings on astronomy and the teachings of Bede and his followers began to be studied in earnest during the revival of learning sponsored by the emperor Charlemagne. By the 9th century rudimentary techniques for calculating the position of the planets were circulating in Western Europe; medieval scholars recognized their flaws, but texts describing these techniques continued to be copied, reflecting an interest in the motions of the planets and in their astrological significance.

Building on this astronomical background, in the 10th century European scholars such as Gerbert of Aurillac began to travel to Spain and Sicily to seek out learning which they had heard existed in the Arabic-speaking world. There they first encountered various practical astronomical techniques concerning the calendar and timekeeping, most notably those dealing with the astrolabe. Soon scholars such as Hermann of Reichenau were writing texts in Latin on the uses and construction of the astrolabe and others, such as Walcher of

Malvern, were using the astrolabe to observe the time of eclipses in order to test the validity of computistical tables.

By the 12th century, scholars were traveling to Spain and Sicily to seek out more advanced astronomical and astrological texts, which they translated into Latin from Arabic and Greek to further enrich the astronomical knowledge of Western Europe. The arrival of these new texts coincided with the rise of the universities in medieval Europe, in which they soon found a home. Reflecting the introduction of astronomy into the universities, John of Sacrobosco wrote a series of influential introductory astronomy textbooks: the Sphere, a Computus, a text on the Quadrant, and another on Calculation.

In the 14th century, Nicole Oresme, later bishop of Liseux, showed that neither the scriptural texts nor the physical arguments advanced against the movement of the Earth were demonstrative and adduced the argument of simplicity for the theory that the Earth moves, and *not* the heavens. However, he concluded "everyone maintains, and I think myself, that the heavens do move and not the earth: For God hath established the world which shall not be moved." In the 15th century, Cardinal Nicholas of Cusa suggested in some of his scientific writings that the Earth revolved around the Sun, and that each star is itself a distant sun.

Copernican Revolution

During the renaissance period, astronomy began to undergo a revolution in thought known as the Copernican Revolution, which gets the name from the astronomer Nicolaus Copernicus, who proposed a heliocentric system, in which the planets revolved around the Sun and not the Earth. His *De revolutionibus orbium coelestium* was published in 1543. While in the long term this was a very controversial claim, in the very beginning it only brought minor controversy. The theory became the dominant view because many figures, most notably Galileo Galilei, Johannes Kepler and Isaac Newton championed and improved upon the work. Other figures also aided this new model despite not believing the overall theory, like Tycho Brahe, with his well-known observations.

Brahe, a Danish noble, was an essential astronomer in this period. He came on the astronomical scene with the publication of *De nova stella*, in which he disproved conventional wisdom on the supernova SN 1572 (As bright as Venus at its peak, SN 1572 later became invisible to the naked eye, disproving the Aristotelian doctrine of the immutability of the heavens.) He also created the Tychonic system, where the Sun and Moon and the stars revolve around the Earth, but the other five planets revolve around the Sun. This system blended the mathematical benefits of the Copernican system with the "physical benefits" of the Ptolemaic system. This was one of the systems people believed in when they did not accept heliocentrism, but could no longer accept the Ptolemaic system. He is most known for his highly accurate observations of the stars and the solar system. Later he moved to Prague and continued his work. In Prague he was at work on the Rudolphine Tables, that were not finished until after his death. The Rudolphine Tables was a star map designed to be more accurate than either the Alfonsine tables, made in the 1300s, and the Prutenic Tables, which were inaccurate. He was assisted at this time by his assistant Johannes Kepler, who would later use his observations to finish Brahe's works and for his theories as well.

After the death of Brahe, Kepler was deemed his successor and was given the job of completing Brahe's uncompleted works, like the Rudolphine Tables. He completed the Rudolphine Tables in 1624, although it was not published for several years. Like many other figures of this era, he was subject to religious and political troubles, like the Thirty Years' War, which led to chaos that almost destroyed some of his works. Kepler was, however, the first to attempt to derive mathematical predictions of celestial motions from assumed physical causes. He discovered the three Kepler's laws of planetary motion that now carry his name, those laws being as follows:

- The orbit of a planet is an ellipse with the Sun at one of the two foci.
- A line segment joining a planet and the Sun sweeps out equal areas during equal intervals of time.
- The square of the orbital period of a planet is proportional to the cube of the semi-major axis of its orbit.

With these laws, he managed to improve upon the existing heliocentric model. The first two were published in 1609. Kepler's contributions improved upon the overall system, giving it more credibility because it adequately explained events and could cause more reliable predictions. Before this, the Copernican model was just as unreliable as the Ptolemaic model. This improvement came because Kepler realized the orbits were not perfect circles, but ellipses.

Galileo Galilei was among the first to use a telescope to observe the sky, and after constructing a 20x refractor telescope. He discovered the four largest moons of Jupiter in 1610, which are now collectively known as the Galilean moons, in his honor. This discovery was the first known observation of satellites orbiting another planet. He also found that our Moon had craters and observed, and correctly explained, sunspots, and that Venus exhibited a full set of phases resembling lunar phases. Galileo argued that these facts demonstrated incompatibility with the Ptolemaic model, which could not explain the phenomenon and would even contradict it. With the moons it demonstrated that the Earth does not have to have everything orbiting it and that other parts of the Solar System could orbit another object, such as the Earth orbiting the Sun. In the Ptolemaic system the celestial bodies were supposed to be perfect so such objects should not have craters or sunspots. The phases of Venus could only happen in the event that Venus' orbit is insides Earth's orbit, which could not happen if the Earth was the center. He, as the most famous example, had to face challenges from church officials, more specifically the Roman Inquisition. They accused him of heresy because these beliefs went against the teachings of the Roman Catholic Church and were challenging the Catholic church's authority when it was at its weakest. While he was able to avoid punishment for a little while he was eventually tried and pled guilty to heresy in 1633. Although this came at some expense, his book was banned, and he was put under house arrest until he died in 1642.

Sir Isaac Newton developed further ties between physics and astronomy through his law of universal gravitation. Realizing that the same force that attracts objects to the surface of the Earth held the Moon in orbit around the Earth, Newton was able to explain – in one theoretical framework – all known gravitational phenomena. In his *Philosophiæ Naturalis Principia Mathematica*, he derived Kepler's laws from first principles. Those first principles are as follows:

- In an inertial frame of reference, an object either remains at rest or continues to move at constant velocity, unless acted upon by a force.
- In an inertial reference frame, the vector sum of the forces F on an object is equal to the mass m of that object multiplied by the acceleration a of the object: F = ma. (It is assumed here that the mass m is constant)
- When one body exerts a force on a second body, the second body simultaneously exerts a force equal in magnitude and opposite in direction on the first body.

Thus while Kepler explained how the planets moved, Newton accurately managed to explain why the planets moved the way they do. Newton's theoretical developments laid many of the foundations of modern physics.

Completing the Solar System

Outside of England, Newton's theory took some time to become established. Descartes' theory of vortices held sway in France, and Huygens, Leibniz and Cassini accepted only parts of Newton's system, preferring their own philosophies. Voltaire published a popular account in 1738. In 1748, the French Academy of Sciences offered a reward for solving the perturbations of Jupiter and Saturn which was eventually solved by Euler and Lagrange. Laplace completed the theory of the planets, publishing from 1798 to 1825. The early origins of the solar nebular model of planetary formation had begun.

Edmund Halley succeeded Flamsteed as Astronomer Royal in England and succeeded in predicting the return in 1758 of the comet that bears his name. Sir William Herschel found the first new planet, Uranus, to be observed in modern times in 1781. The gap between the planets Mars and Jupiter disclosed by the Titius–Bode law was filled by the discovery of the asteroids Ceres and 2 Pallas Pallas in 1801 and 1802 with many more following.

At first, astronomical thought in America was based on Aristotelian philosophy, but interest in the new astronomy began to appear in Almanacs as early as 1659.

Modern astronomy

In the 19th century, Joseph von Fraunhofer discovered that when sunlight was dispersed, a multitude of spectral lines were observed (regions where there was less or no light). Experiments with hot gases showed that the same lines could be observed in the spectra of gases, with specific lines corresponding to unique elements. It was proved that the chemical elements found in the Sun (chiefly hydrogen and helium) were also found on Earth. During the 20th century spectroscopy (the study of these lines) advanced, especially because of the advent of quantum physics, which was necessary to understand the observations.

- Celebrating diversity

Although in previous centuries noted astronomers were exclusively male, at the turn of the 20th century women began to play a role in the great discoveries. In this period prior to modern computers, women at the United States Naval Observatory (USNO), Harvard University, and other astronomy research institutions began to be hired as human "computers", who performed the tedious calculations while scientists performed research requiring more background knowledge. A number of discoveries in this period were originally noted by the women "computers" and reported to their supervisors. For example, at the Harvard Observatory Henrietta Swan Leavitt discovered the cepheid variable star period-luminosity relation which she further developed into a method of measuring distance outside of the Solar System.

Annie Jump Cannon, also at Harvard, organized the stellar spectral types according to stellar temperature. In 1847, Maria Mitchell discovered a comet using a telescope. According to Lewis D. Eigen, Cannon alone, "in only 4 years discovered and catalogued more stars than all the men in history put together." Most of these women received little or no recognition during their lives due to their lower professional standing in the field of astronomy. Although their discoveries and methods are taught in classrooms around the world, few students of astronomy can attribute the works to their authors or have any idea that there were active female astronomers at the end of the 19th century.

Cosmology and the expansion of the universe

Most of our current knowledge was gained during the 20th century. With the help of the use of photography, fainter objects were observed. The Sun was found to be part of a galaxy made up of more than 10 stars (10 billion stars). The existence of other galaxies, one of the matters of *the great debate*, was settled by Edwin Hubble, who identified the Andromeda nebula as a different galaxy, and many others at large distances and receding, moving away from our galaxy.

Physical cosmology, a discipline that has a large intersection with astronomy, made huge advances during the 20th century, with the model of the hot Big Bang heavily supported by the evidence provided by astronomy and physics, such as the redshifts of very distant galaxies and radio sources, the cosmic microwave background radiation, Hubble's law and cosmological abundances of elements.

New windows into the Cosmos open

In the 19th century, scientists began discovering forms of light which were invisible to the naked eye: X-Rays, gamma rays, radio waves, microwaves, ultraviolet radiation, and infrared radiation. This had a major impact on astronomy, spawning the fields of infrared astronomy, radio astronomy, x-ray astronomy and finally gamma-ray astronomy. With the advent of spectroscopy it was proven that other stars were similar to the Sun, but with a range of temperatures, masses and sizes. The existence of our galaxy, the Milky Way, as a separate group of stars was only proven in the 20th century, along with the existence of "external" galaxies, and soon after, the expansion of the universe seen in the recession of most galaxies from us.

Chapter 20

History of Chemistry

The **history of chemistry** represents a time span from ancient history to the present. By 1000 BC, civilizations used technologies that would eventually form the basis of the various branches of chemistry. Examples include the discovery of fire, extracting metals from ores, making pottery and glazes, fermenting beer and wine, extracting chemicals from plants for medicine and perfume, rendering fat into soap, making glass, and making alloys like bronze.

The protoscience of chemistry, alchemy, was unsuccessful in explaining the nature of matter and its transformations. However, by performing experiments and recording the results, alchemists set the stage for modern chemistry. The distinction began to emerge when a clear differentiation was made between chemistry and alchemy by Robert Boyle in his work *The Sceptical Chymist* (1661). While both alchemy and chemistry are concerned with matter and its transformations, chemists are seen as applying scientific method to their work.

The history of chemistry is intertwined with the history of thermodynamics, especially through the work of Willard Gibbs.

Ancient history

Early humans

A 100,000-year-old ochre-processing workshop was found at Blombos Cave in South Africa. It indicates that early humans had an elementary knowledge of chemistry. Paintings drawn by early humans consisting of early humans mixing animal blood with other liquids found on cave walls also indicate a small knowledge of chemistry.

Early metallurgy

The earliest recorded metal employed by humans seems to be gold, which can be found free or "native". Small amounts of natural gold have been found in Spanish caves used during the late Paleolithic period, around 40,000 BC.

Silver, copper, tin and meteoric iron can also be found native, allowing a limited amount of metalworking in ancient cultures. Egyptian weapons made from meteoric iron in about 3000 BC were highly prized as "daggers from Heaven".

Arguably the first chemical reaction used in a controlled manner was fire. However, for millennia fire was seen simply as a mystical force that could transform one substance into another (burning wood, or boiling water) while producing heat and light. Fire affected many aspects of early societies. These ranged from the simplest facets of everyday life, such as cooking and habitat heating and lighting, to more advanced uses, such as for making pottery and bricks and melting of metals to make tools.

It was fire that led to the discovery of glass and the purification of metals; this was followed by the rise of metallurgy. During the early stages of metallurgy, methods of purification of metals were sought, and gold, known in ancient Egypt as early as 2900 BC, became a precious metal.

Bronze Age

- Certain metals can be recovered from their ores by simply heating the rocks in a fire: notably tin, lead and (at a higher temperature) copper. This process is known as smelting. The first evidence of this extractive metallurgy dates from the 6th and 5th millennia BC, and was found in the archaeological sites of Majdanpek, Yarmovac and Plocnik, all three in Serbia. To date, the earliest copper smelting is found at the Belovode site; these examples include a copper axe from 5500 BC belonging to the Vinča culture. Other signs of early metals are found from the third millennium BC in places like Palmela (Portugal), Los Millares (Spain), and Stonehenge (United Kingdom). However, as often happens in the study of prehistoric times, the ultimate beginnings cannot be clearly defined and new discoveries are ongoing.

These first metals were single elements, or else combinations as naturally occurred. By combining copper and tin, a superior metal could be made, an alloy called bronze. This was a major technological shift which began the Bronze Age about 3500 BC. The Bronze Age was a period in human cultural development when the most advanced metalworking (at least in systematic and widespread use) included techniques for smelting copper and tin from naturally occurring outcroppings of copper ores, and then smelting those ores to cast bronze. These naturally occurring ores typically included arsenic as a common impurity. Copper/tin ores are rare, as reflected in the absence of tin bronzes in western Asia before 3000 BC.

After the Bronze Age, the history of metallurgy was marked by armies seeking better weaponry. States in Eurasia prospered when they made the superior alloys, which, in turn, made better armor and better weapons. Significant progress in metallurgy and alchemy was made in ancient India.

Iron Age

The extraction of iron from its ore into a workable metal is much more difficult than copper or tin. While iron is not better suited for tools than bronze (until steel was discovered), iron ore is much more abundant and common than either copper or tin, and therefore more often available locally, with no need to trade for it.

Iron working appears to have been invented by the Hittites in about 1200 BC, beginning the Iron Age. The secret of extracting and working iron was a key factor in the success of the Philistines.

The Iron Age refers to the advent of iron working (ferrous metallurgy). Historical developments in ferrous metallurgy can be found in a wide variety of past cultures and civilizations. These include the ancient and medieval kingdoms and empires of the Middle East and Near East, ancient Iran, ancient Egypt, ancient Nubia, and Anatolia (Turkey), Ancient Nok, Carthage, the Greeks and Romans of ancient Europe, medieval Europe, ancient and medieval China, ancient and medieval India, ancient and medieval Japan, amongst others. Many applications, practices, and devices associated with or involved in metallurgy were established in ancient China, such as the innovation of the blast furnace, cast iron, hydraulic-powered trip hammers, and double-acting piston bellows.

Classical antiquity and atomism

Philosophical attempts to rationalize why different substances have different properties (color, density, smell), exist in different states (gaseous, liquid, and solid), and react in a different manner when exposed to environments, for example to water or fire or temperature changes, led ancient philosophers to postulate the first theories on nature and chemistry. The history of such philosophical theories that relate to chemistry can probably be traced back to every single ancient civilization. The common aspect in all these theories was the attempt to identify a small number of primary classical elements that make up all the various substances in nature. Substances like air, water, and soil/earth, energy forms, such as fire and light, and more abstract concepts such as thoughts, aether, and heaven, were common in ancient civilizations even in the absence of any cross-fertilization: for example ancient Greek, Indian, Mayan, and Chinese philosophies all considered air, water, earth and fire as primary elements.

Ancient world

Around 420 BC, Empedocles stated that all matter is made up of four elemental substances: earth, fire, air and water. The early theory of atomism can be traced back to ancient Greece and ancient India. Greek atomism dates back to the Greek philosopher Democritus, who declared that matter is composed of indivisible and indestructible particles called "atomos" around 380 BC. Leucippus also declared that atoms were the most indivisible part of matter. This coincided with a similar declaration by Indian philosopher Kanada in his Vaisheshika sutras around the same time period. In much the same fashion he discussed the existence of gases. What Kanada declared by sutra, Democritus declared by philosophical musing. Both suffered from a lack of empirical data. Without scientific proof, the existence of atoms was easy to deny. Aristotle opposed the existence of atoms in 330 BC. Earlier, in 380 BC, a Greek text attributed to Polybus argued that the human body is composed of four humours. Around 300 BC, Epicurus postulated a universe of indestructible atoms in which man himself is responsible for achieving a balanced life.

With the goal of explaining Epicurean philosophy to a Roman audience, the Roman poet and philosopher Lucretius wrote *De rerum natura* (The Nature of Things) in 50 BC. In the work, Lucretius presents the principles of atomism; the nature of the mind and soul; explanations of sensation and thought; the development of the world and its phenomena; and explains a variety of celestial and terrestrial phenomena.

Much of the early development of purification methods is described by Pliny the Elder in his Naturalis Historia. He tried to explain those methods, as well as making acute observations of the state of many minerals.

Medieval alchemy

The elemental system used in medieval alchemy was developed primarily by the Persian-Arab alchemist Jābir ibn Hayyān and was rooted in the classical elements of Greek tradition. His system consisted of the four Aristotelian elements of air, earth, fire, and water in addition to two philosophical elements: sulphur, characterizing the principle of combustibility, "the stone which burns"; and mercury, characterizing the principle of metallic properties. They were seen by early alchemists as idealized expressions of irreducible components of the universe and are of larger consideration within philosophical alchemy.

The three metallic principles (sulphur to flammability or combustion, mercury to volatility and stability, and salt to solidity) became the *tria prima* of the Swiss alchemist Paracelsus. He reasoned that Aristotle's four-element theory appeared in bodies as three principles. Paracelsus saw these principles as fundamental and justified them by recourse to the description of how wood burns in fire. Mercury included the cohesive principle, so that when it left the wood (in smoke) the wood fell apart. Smoke described the volatility (the mercurial principle), the heat-giving flames described flammability (sulphur), and the remnant ash described solidity (salt).

The philosopher's stone

Alchemy is defined by the Hermetic quest for the philosopher's stone, the study of which is steeped in symbolic mysticism, and differs greatly from modern science. Alchemists toiled to make transformations on an esoteric (spiritual) and/or exoteric (practical) level. It was the protoscientific, exoteric aspects of alchemy that contributed heavily to the evolution of chemistry in Greco-Roman Egypt, in the Islamic Golden Age, and then in Europe. Alchemy and chemistry share an interest in the composition and properties of matter, and until the 18th century they were not separate disciplines. The term *chymistry* has been used to describe the blend of alchemy and chemistry that existed before that time.

The earliest Western alchemists, who lived in the first centuries of the common era, invented chemical apparatus. The *bain-marie*, or water bath, is named for Mary the Jewess. Her work also gives the first descriptions of the *tribikos* and *kerotakis*. Cleopatra the Alchemist described furnaces and has been credited with the invention of the alembic. Later, the experimental framework established by Jabir ibn Hayyan influenced alchemists as the discipline migrated through the Islamic world, then to Europe in the 12th century CE.

During the Renaissance, exoteric alchemy remained popular in the form of Paracelsian iatrochemistry, while spiritual alchemy flourished, realigned to its Platonic, Hermetic, and Gnostic roots. Consequently, the symbolic quest for the philosopher's stone was not superseded by scientific advances, and was still the domain of respected scientists and doctors until the early 18th century. Early modern alchemists who are renowned for their scientific contributions include Jan Baptist van Helmont, Robert Boyle, and Isaac Newton.

Alchemy in the Islamic world

In the Islamic World, the Muslims were translating the works of ancient Greek and Hellenistic philosophers into Arabic and were experimenting with scientific ideas. The Arabic works attributed to the 8th-century alchemist Jābir ibn Hayyān introduced a systematic classification of chemical substances, and provided instructions for deriving an inorganic compound (sal ammoniac or ammonium chloride) from organic substances (such as plants, blood, and hair) by chemical means. Some Arabic Jabirian works (e.g., the "Book of Mercy", and the "Book of Seventy") were later translated into Latin under the Latinized name "Geber", and in 13th-century Europe an anonymous writer, usually referred to as pseudo-Geber, started to produce alchemical and metallurgical writings under this name. Later influential Muslim philosophers, such as Abū al-Rayhān al-Bīrūnī and Avicenna disputed the theories of alchemy, particularly the theory of the transmutation of metals.

Problems encountered with alchemy

There were several problems with alchemy, as seen from today's standpoint. There was no systematic naming scheme for new compounds, and the language was esoteric and vague to the point that the terminologies meant different things to different people. In fact, according to *The Fontana History of Chemistry* (Brock, 1992):

The language of alchemy soon developed an arcane and secretive technical vocabulary designed to conceal information from the uninitiated. To a large degree, this language is incomprehensible to us today, though it is apparent that readers of Geoffery Chaucer's Canon's Yeoman's Tale or audiences of Ben Jonson's The Alchemist were able to construe it sufficiently to laugh at it.

Chaucer's tale exposed the more fraudulent side of alchemy, especially the manufacture of counterfeit gold from cheap substances. Less than a century earlier, Dante Alighieri also demonstrated an awareness of this fraudulence, causing him to consign all alchemists to the Inferno in his writings. Soon afterwards, in 1317, the Avignon Pope John XXII ordered all alchemists to leave France for making counterfeit money. A law was passed in England in 1403 which made the "multiplication of metals" punishable by death. Despite these and other apparently extreme measures, alchemy did not die. Royalty and privileged classes still sought to discover the philosopher's stone and the elixir of life for themselves.

There was also no agreed-upon scientific method for making experiments reproducible. Indeed, many alchemists included in their methods irrelevant information such as the timing of the tides or the phases of the moon. The esoteric nature and codified vocabulary of alchemy appeared to be more useful in concealing the fact that they could not be sure of very much at all. As early as the 14th century, cracks seemed to grow in the facade of alchemy; and people became sceptical. Clearly, there needed to be a scientific method in which experiments could be repeated by other people, and results needed to be reported in a clear language that laid out both what was known and what was unknown.

17th and 18th centuries: Early chemistry

Practical attempts to improve the refining of ores and their extraction to smelt metals was an important source of information for early chemists in the 16th century, among them Georg Agricola (1494–1555), who published his great work *De re metallica* in 1556. His work describes the highly developed and complex processes of mining metal ores, metal extraction and metallurgy of the time. His approach removed the mysticism associated with the subject, creating the practical base upon which others could build. The work describes the many kinds of furnace used to smelt ore, and stimulated interest in minerals and their composition. It is no coincidence that he gives numerous references to the earlier author, Pliny the Elder and his *Naturalis Historia*. Agricola has been described as the "father of metallurgy".

In 1605, Sir Francis Bacon published *The Proficience and Advancement of Learning*, which contains a description of what would later be known as the scientific method. In 1605, Michal Sedziwój publishes the alchemical treatise *A New Light of Alchemy* which proposed the existence of the "food of life" within air, much later recognized as oxygen. In 1615 Jean Beguin published the *Tyrocinium Chymicum*, an early chemistry textbook, and in it draws the first-ever chemical equation. In

1637 René Descartes publishes *Discours de la méthode*, which contains an outline of the scientific method.

The Dutch chemist Jan Baptist van Helmont's work *Ortus medicinae* was published posthumously in 1648; the book is cited by some as a major transitional work between alchemy and chemistry, and as an important influence on Robert Boyle. The book contains the results of numerous experiments and establishes an early version of the law of conservation of mass. Working during the time just after Paracelsus and iatrochemistry, Jan Baptist van Helmont suggested that there are insubstantial substances other than air and coined a name for them - "gas", from the Greek word *chaos*. In addition to introducing the word "gas" into the vocabulary of scientists, van Helmont conducted several experiments involving gases. Jan Baptist van Helmont is also remembered today largely for his ideas on spontaneous generation and his 5-year tree experiment, as well as being considered the founder of pneumatic chemistry.

Robert Boyle

Anglo-Irish chemist Robert Boyle (1627–1691) is considered to have refined the modern scientific method for alchemy and to have separated chemistry further from alchemy. Although his research clearly has its roots in the alchemical tradition, Boyle is largely regarded today as the first modern chemist, and therefore one of the founders of modern chemistry, and one of the pioneers of modern experimental scientific method. Although Boyle was not the original discoverer, he is best known for Boyle's law, which he presented in 1662: the law describes the inversely proportional relationship between the absolute pressure and volume of a gas, if the temperature is kept constant within a closed system.

Boyle is also credited for his landmark publication *The Sceptical Chymist* in 1661, which is seen as a cornerstone book in the field of chemistry. In the work, Boyle presents his hypothesis that every phenomenon was the result of collisions of particles in motion. Boyle appealed to chemists to experiment and asserted that experiments denied the limiting of chemical elements to only the classic four: earth, fire, air, and water. He also pleaded that chemistry should cease to be subservient to medicine or to alchemy, and rise to the status of a science. Importantly, he advocated a rigorous approach to scientific experiment: he believed all theories must be proved experimentally before being regarded as true. The work contains some of the earliest modern ideas of atoms, molecules, and chemical reaction, and marks the beginning of the history of modern chemistry.

Boyle also tried to purify chemicals to obtain reproducible reactions. He was a vocal proponent of the mechanical philosophy proposed by René Descartes to explain and quantify the physical properties and interactions of material substances. Boyle was an atomist, but favoured the word *corpuscle* over *atoms*. He commented that the finest division of matter where the properties are retained is at the level of corpuscles. He also performed numerous investigations with an air pump, and noted that the mercury fell as air was pumped out. He also observed that pumping the air out of a container would extinguish a flame and kill small animals placed inside. Boyle helped to lay the foundations for the Chemical Revolution with his mechanical corpuscular philosophy. Boyle repeated the tree experiment of van Helmont, and was the first to use indicators which changed colors with acidity.

Development and dismantling of phlogiston

In 1702, German chemist Georg Stahl coined the name "phlogiston" for the substance believed to be released in the process of burning. Around 1735, Swedish chemist Georg Brandt analyzed a dark blue pigment found in copper ore. Brandt demonstrated that the pigment contained a new element, later named cobalt. In 1751, a Swedish chemist and pupil of Stahl's named Axel Fredrik Cronstedt, identified an impurity in copper ore as a separate metallic element, which he named nickel. Cronstedt is one of the founders of modern mineralogy. Cronstedt also discovered the mineral scheelite in 1751, which he named tungsten, meaning "heavy stone" in Swedish.

In 1754, Scottish chemist Joseph Black isolated carbon dioxide, which he called "fixed air". In 1757, Louis Claude Cadet de Gassicourt, while investigating arsenic compounds, creates Cadet's fuming liquid, later discovered to be cacodyl oxide, considered to be the first synthetic organometallic compound. In 1758, Joseph Black formulated the concept of latent heat to explain the thermochemistry of phase changes. In 1766, English chemist Henry Cavendish isolated hydrogen, which he called "inflammable air". Cavendish discovered hydrogen as a colorless, odourless gas that burns and can form an explosive mixture with air, and published a paper on the production of water by burning inflammable air (that is, hydrogen) in dephlogisticated air (now known to be oxygen), the latter a constituent of atmospheric air (phlogiston theory).

In 1773, Swedish chemist Carl Wilhelm Scheele discovered oxygen, which he called "fire air", but did not immediately publish his achievement. In 1774, English chemist Joseph Priestley independently isolated oxygen in its gaseous state, calling it "dephlogisticated air", and published his work before Scheele. During his lifetime, Priestley's considerable scientific reputation rested on his invention of soda water, his writings on electricity, and his discovery of several "airs" (gases), the most famous being what Priestley dubbed "dephlogisticated air" (oxygen). However, Priestley's determination to defend phlogiston theory and to reject what would become the chemical revolution eventually left him isolated within the scientific community.

In 1781, Carl Wilhelm Scheele discovered that a new acid, tungstic acid, could be made from Cronstedt's scheelite (at the time named tungsten). Scheele and Torbern Bergman suggested that it might be possible to obtain a new metal by reducing this acid. In 1783, José and Fausto Elhuyar found an acid made from wolframite that was identical to tungstic acid. Later that year, in Spain, the brothers succeeded in isolating the metal now known as tungsten by reduction of this acid with charcoal, and they are credited with the discovery of the element.

Volta and the Voltaic pile

Italian physicist Alessandro Volta constructed a device for accumulating a large charge by a series of inductions and groundings. He investigated the 1780s discovery "animal electricity" by Luigi Galvani, and found that the electric current was generated from the contact of dissimilar metals, and that the frog leg was only acting as a detector. Volta demonstrated in 1794 that when two metals and brine-soaked cloth or cardboard are arranged in a circuit they produce an electric current.

In 1800, Volta stacked several pairs of alternating copper (or silver) and zinc discs (electrodes) separated by cloth or cardboard soaked in brine (electrolyte) to increase the electrolyte conductivity. When the top and bottom contacts were connected by a wire, an electric current flowed through this voltaic pile and the connecting wire. Thus, Volta is credited with constructing the first electrical battery to produce electricity.

Thus, Volta is considered to be the founder of the discipline of electrochemistry. A Galvanic cell (or voltaic cell) is an electrochemical cell that derives electrical energy from a spontaneous redox reaction taking place within the cell. It generally consists of two different metals connected by a salt bridge, or individual half-cells separated by a porous membrane.

Antoine-Laurent de Lavoisier

- Antoine-Laurent de Lavoisier demonstrated with careful measurements that transmutation of water to earth was not possible, but that the sediment observed from boiling water came from the container. He burnt phosphorus and sulfur in air, and proved

> that the products weighed more than the original samples, with the mass gained being lost from the air. Thus, in 1789, he established the Law of Conservation of Mass, which is also called "Lavoisier's Law."

Repeating the experiments of Priestley, he demonstrated that air is composed of two parts, one of which combines with metals to form calxes. In *Considérations Générales sur la Nature des Acides* (1778), he demonstrated that the "air" responsible for combustion was also the source of acidity. The next year, he named this portion oxygen (Greek for acid-former), and the other azote (Greek for no life). Because of his more thorough characterization of it as an element, Lavoisier thus has a claim to the discovery of oxygen along with Priestley and Scheele. He also discovered that the "inflammable air" discovered by Cavendish - which he termed hydrogen (Greek for water-former) - combined with oxygen to produce a dew, as Priestley had reported, which appeared to be water. In *Reflexions sur le Phlogistique* (1783), Lavoisier showed the phlogiston theory of combustion to be inconsistent. Mikhail Lomonosov independently established a tradition of chemistry in Russia in the 18th century; he also rejected the phlogiston theory, and anticipated the kinetic theory of gases. Lomonosov regarded heat as a form of motion, and stated the idea of conservation of matter.

Lavoisier worked with Claude Louis Berthollet and others to devise a system of chemical nomenclature, which serves as the basis of the modern system of naming chemical compounds. In his *Methods of Chemical Nomenclature* (1787), Lavoisier invented the system of naming and classification still largely in use today, including names such as sulfuric acid, sulfates, and sulfites. In 1785, Berthollet was the first to introduce the use of chlorine gas as a commercial bleach. In the same year he first determined the elemental composition of the gas ammonia. Berthollet first produced a modern bleaching liquid in 1789 by passing chlorine gas through a solution of sodium carbonate - the result was a weak solution of sodium hypochlorite. Another strong chlorine oxidant and bleach which he investigated and was the first to produce, potassium chlorate ($KClO_3$), is known as Berthollet's Salt. Berthollet is also known for his scientific contributions to the theory of chemical equilibrium via the mechanism of reversible reactions.

Lavoisier's *Traité Élémentaire de Chimie* (Elementary Treatise of Chemistry, 1789) was the first modern chemical textbook, and presented a unified view of new theories of chemistry, contained a clear statement of the Law of Conservation of Mass, and denied the existence of phlogiston. In addition, it contained a list of elements, or substances that could not be broken down further, which included oxygen, nitrogen, hydrogen, phosphorus, mercury, zinc, and sulfur. His list, however, also included light and caloric, which he believed to be material substances. In the work, Lavoisier underscored the observational basis of his chemistry, stating "I have tried...to arrive at the truth by linking up facts; to suppress as much as possible the use of reasoning, which is often an unreliable instrument which deceives us, in order to follow as much as possible the torch of observation and of experiment." Nevertheless, he believed that the real existence of atoms was philosophically impossible. Lavoisier demonstrated that organisms disassemble and reconstitute atmospheric air in the same manner as a burning body.

With Pierre-Simon Laplace, Lavoisier used a calorimeter to estimate the heat evolved per unit of carbon dioxide produced. They found the same ratio for a flame and animals, indicating that animals produced energy by a type of combustion. Lavoisier believed in the radical theory, which stated that radicals, which function as a single group in a chemical reaction, would combine with oxygen in reactions. He believed all acids contained oxygen. He also discovered that diamond is a crystalline form of carbon.

Although many of Lavoisier's partners were influential for the advancement of chemistry as a scientific discipline, his wife Marie-Anne Lavoisier was arguably the most influential of them all. Upon their marriage, Mme. Lavoisier began to study chemistry, English, and drawing in order to help her husband in his work either by translating papers into English, a language which Lavoisier did not know, or by keeping records and drawing the various apparatuses that Lavoisier used in his labs. Through her ability to read and translate articles from Britain for her husband, Lavoisier had access to knowledge of many of the chemical advances happening outside of his lab. Furthermore, Mme. Lavoisier kept records of her husband's work and ensured that his works were published. The first sign of Marie-Anne's true potential as a chemist in Lavoisier's lab came when she was translating a book by the scientist Richard Kirwan. While translating, she stumbled upon and corrected multiple errors. When she presented her translation, along with her notes, to Lavoisier, her contributions led to Lavoisier's refutation of the theory of phlogiston.

Lavoisier made many fundamental contributions to the science of chemistry. Following his work, chemistry acquired a strict, quantitative nature, allowing reliable predictions to be made. The revolution in chemistry which he brought about was a result of a conscious effort to fit all experiments into the framework of a single theory. He established the consistent use of chemical balance, used oxygen to overthrow the phlogiston theory, and developed a new system of chemical nomenclature. Further potential contributions were cut short when Lavoisier was beheaded during the French Revolution.

19th century

In 1802, French American chemist and industrialist Éleuthère Irénée du Pont, who learned manufacture of gunpowder and explosives under Antoine Lavoisier, founded a gunpowder manufacturer in Delaware known as E. I. du Pont de Nemours and Company. The French Revolution forced his family to move to the United States where du Pont started a gunpowder mill on the Brandywine River in Delaware. Wanting to make the best powder possible, du Pont was vigilant about the quality of the materials he used. For 32 years, du Pont served as president of E. I. du Pont de Nemours and Company, which eventually grew into one of the largest and most successful companies in America.

Throughout the 19th century, chemistry was divided between those who followed the atomic theory of John Dalton and those who did not, such as Wilhelm Ostwald and Ernst Mach. Although such proponents of the atomic theory as Amedeo Avogadro and Ludwig Boltzmann made great advances in explaining the behavior of gases, this dispute was not finally settled until Jean Perrin's experimental investigation of Einstein's atomic explanation of Brownian motion in the first decade of the 20th century.

Well before the dispute had been settled, many had already applied the concept of atomism to chemistry. A major example was the ion theory of Svante Arrhenius which anticipated ideas about atomic substructure that did not fully develop until the 20th century. Michael Faraday was another early worker, whose major contribution to chemistry was electrochemistry, in which (among other things) a certain quantity of electricity during electrolysis or electrodeposition of metals was shown to be associated with certain quantities of chemical elements, and fixed quantities of the elements therefore with each other, in specific ratios. These findings, like those of Dalton's combining ratios, were early clues to the atomic nature of matter.

John Dalton

In 1803, English meteorologist and chemist John Dalton proposed Dalton's law, which describes the relationship between the components in a mixture of gases and the relative pressure each contributes to that of the overall mixture. Discovered in 1801, this concept is also known as Dalton's law of partial pressures.

Dalton also proposed a modern atomic theory in 1803 which stated that all matter was composed of small indivisible particles termed atoms, atoms of a given element possess unique characteristics and weight, and three types of atoms exist: simple (elements), compound (simple molecules), and complex (complex molecules). In 1808, Dalton first published *New System of Chemical Philosophy* (1808-1827), in which he outlined the first modern scientific description of the atomic theory. This work identified chemical elements as a specific type of atom, therefore rejecting Newton's theory of chemical affinities.

Instead, Dalton inferred proportions of elements in compounds by taking ratios of the weights of reactants, setting the atomic weight of hydrogen to be identically one. Following Jeremias Benjamin Richter (known for introducing the term *stoichiometry*), he proposed that chemical elements combine in integral ratios. This is known as the law of multiple proportions or Dalton's law, and Dalton included a clear description of the law in his *New System of Chemical Philosophy*. The law of multiple proportions is one of the basic laws of stoichiometry used to establish the atomic theory. Despite the importance of the work as the first view of atoms as physically real entities and introduction of a system of chemical symbols, *New System of Chemical Philosophy* devoted almost as much space to the caloric theory as to atomism.

French chemist Joseph Proust proposed the law of definite proportions, which states that elements always combine in small, whole number ratios to form compounds, based on several experiments conducted between 1797 and 1804 Along with the law of multiple proportions, the law of definite proportions forms the basis of stoichiometry. The law of definite proportions and constant composition do not prove that atoms exist, but they are difficult to explain without assuming that chemical compounds are formed when atoms combine in constant proportions.

Jöns Jacob Berzelius

A Swedish chemist and disciple of Dalton, Jöns Jacob Berzelius embarked on a systematic program to try to make accurate and precise quantitative measurements and to ensure the purity of chemicals. Along with Lavoisier, Boyle, and Dalton, Berzelius is known as the father of modern chemistry. In 1828 he compiled a table of relative atomic weights, where oxygen was used as a standard, with its weight set at 100, and which included all of the elements known at the time. This work provided evidence in favor of Dalton's atomic theory - that inorganic chemical compounds are composed of atoms combined in whole number amounts. He determined the exact elementary constituents of a large number of compounds; the results strongly supported Proust's Law of Definite Proportions. In discovering that atomic weights are not integer multiples of the weight of hydrogen, Berzelius also disproved Prout's hypothesis that elements are built up from atoms of hydrogen.

Motivated by his extensive atomic weight determinations and in a desire to aid his experiments, he introduced the classical system of chemical symbols and notation with his 1808 publication *Lärbok i Kemien*, in which elements are abbreviated to one or two letters to make a distinct symbol from their Latin name. This system of chemical notation—in which the elements were given simple written labels, such as O for oxygen, or Fe for iron, with proportions denoted by numbers—is the same basic system used today. The only difference is that instead of the subscript number used today (e.g., H_2O), Berzelius used a superscript (HO). Berzelius is credited with identifying the chemical elements silicon, selenium, thorium, and cerium.

Students working in Berzelius's laboratory also discovered lithium and vanadium.

Berzelius developed the radical theory of chemical combination, which holds that reactions occur as stable groups of atoms called radicals are exchanged between molecules. He believed that salts are compounds formed of acids and bases, and discovered that the anions in acids were attracted to a positive electrode (the anode), whereas the cations in a base were attracted to a negative electrode (the cathode). Berzelius did not believe in the Vitalism Theory, but instead in a regulative force which produced organization of tissues in an organism. Berzelius is also credited with originating the chemical terms "catalysis", "polymer", "isomer", and "allotrope", although his original definitions differ dramatically from modern usage. For example, he coined the term "polymer" in 1833 to describe organic compounds which shared identical empirical formulas but which differed in overall molecular weight, the larger of the compounds being described as "polymers" of the smallest. By this long-superseded, pre-structural definition, glucose ($C_6H_{12}O_6$) was viewed as a polymer of formaldehyde (CH_2O).

New elements and gas laws

English chemist Humphry Davy was a pioneer in the field of electrolysis, using Alessandro Volta's voltaic pile to split up common compounds and thus isolate a series of new elements. He went on to electrolyse molten salts and discovered several new metals, especially sodium and potassium, highly reactive elements known as the alkali metals. Potassium, the first metal that was isolated by electrolysis, was discovered in 1807 by Davy, who derived it from caustic potash (KOH). Before the 19th century, no distinction was made between potassium and sodium. Sodium was first isolated by Davy in the same year by passing an electric current through molten sodium hydroxide (NaOH). When Davy heard that Berzelius and Pontin prepared calcium amalgam by electrolyzing lime in mercury, he tried it himself. Davy was successful, and discovered calcium in 1808 by electrolyzing a mixture of lime and mercuric oxide. He worked with electrolysis throughout his life and, in 1808, he isolated magnesium, strontium and barium.

Davy also experimented with gases by inhaling them. This experimental procedure nearly proved fatal on several occasions, but led to the discovery of the unusual effects of nitrous oxide, which came to be known as laughing gas. Chlorine was discovered in 1774 by Swedish chemist Carl Wilhelm Scheele, who called it *"dephlogisticated marine acid"* (see phlogiston theory) and mistakenly thought it contained oxygen. Scheele observed several properties of chlorine gas, such as its bleaching effect on litmus, its deadly effect on insects, its yellow-green colour, and the similarity of its smell to that of aqua regia. However, Scheele was unable to publish his findings at the time. In 1810, chlorine was given its current name by Humphry Davy (derived from the Greek word for green), who insisted that chlorine was in fact an element. He also showed that oxygen could not be obtained from the substance known as oxymuriatic acid (HCl solution). This discovery overturned Lavoisier's definition of acids as compounds of oxygen. Davy was a popular lecturer and able experimenter.

French chemist Joseph Louis Gay-Lussac shared the interest of Lavoisier and others in the quantitative study of the properties of gases. From his first major program of research in 1801–1802, he concluded that equal volumes of all gases expand equally with the same increase in temperature: this conclusion is usually called "Charles's law", as Gay-Lussac gave credit to Jacques Charles, who had arrived at nearly the same conclusion in the 1780s but had not published it. The law was independently discovered by British natural philosopher John Dalton by 1801, although Dalton's description was less thorough than Gay-Lussac's. In 1804 Gay-Lussac made several daring ascents of over 7,000 meters above sea level in hydrogen-filled balloons—a feat not equaled for another 50 years—that allowed him to investigate other aspects of gases. Not only did he gather magnetic measurements at various altitudes, but he also took pressure, temperature, and humidity measurements and samples of air, which he later analyzed chemically.

In 1808 Gay-Lussac announced what was probably his single greatest achievement: from his own and others' experiments he deduced that gases at constant temperature and pressure combine in simple numerical proportions by volume, and the resulting product or products—if gases—also bear a simple proportion by volume to the volumes of the reactants. In other words, gases under equal conditions of temperature and pressure react with one another in volume ratios of small whole numbers. This conclusion subsequently became known as "Gay-Lussac's law" or the "Law of Combining Volumes". With his fellow professor at the École Polytechnique, Louis Jacques Thénard, Gay-Lussac also participated in early electrochemical research, investigating the elements discovered by its means.

Among other achievements, they decomposed boric acid by using fused potassium, thus discovering the element boron. The two also took part in contemporary debates that modified Lavoisier's definition of acids and furthered his program of analyzing organic compounds for their oxygen and hydrogen content.

The element iodine was discovered by French chemist Bernard Courtois in 1811. Courtois gave samples to his friends, Charles Bernard Desormes (1777–1862) and Nicolas Clément (1779–1841), to continue research. He also gave some of the substance to Gay-Lussac and to physicist André-Marie Ampère. On December 6, 1813, Gay-Lussac announced that the new substance was either an element or a compound of oxygen. It was Gay-Lussac who suggested the name *"iode"*, from the Greek word ιώδες (iodes) for violet (because of the color of iodine vapor). Ampère had given some of his sample to Humphry Davy. Davy did some experiments on the substance and noted its similarity to chlorine. Davy sent a letter dated December 10 to the Royal Society of London stating that he had identified a new element. Arguments erupted between Davy and Gay-Lussac over who identified iodine first, but both scientists acknowledged Courtois as the first to isolate the element.

In 1815, Humphry Davy invented the Davy lamp, which allowed miners within coal mines to work safely in the presence of flammable gases. There had been many mining explosions caused by firedamp or methane often ignited by open flames of the lamps then used by miners. Davy conceived of using an iron gauze to enclose a lamp's flame, and so prevent the methane burning inside the lamp from passing out to the general atmosphere. Although the idea of the safety lamp had already been demonstrated by William Reid Clanny and by the then unknown (but later very famous) engineer George Stephenson, Davy's use of wire gauze to prevent the spread of flame was used by many other inventors in their later designs. There was some discussion as to whether Davy had discovered the principles behind his lamp without the help of the work of Smithson Tennant, but it was generally agreed that the work of both men had been independent. Davy refused to patent the lamp, and its invention led to him being awarded the Rumford medal in 1816.

After Dalton published his atomic theory in 1808, certain of his central ideas were soon adopted by most chemists. However, uncertainty persisted for half a century about how atomic theory was to be configured and applied to concrete situations; chemists in different countries developed several different incompatible atomistic systems. A paper that suggested a way out of this difficult situation was published as early as 1811 by the Italian physicist Amedeo Avogadro (1776-1856), who hypothesized that equal volumes of gases at the same temperature and pressure contain equal numbers of molecules, from which it followed that relative molecular weights of any two gases are the same as the ratio of the densities of the two gases under the same conditions of temperature and pressure. Avogadro also reasoned that simple gases were not formed of solitary atoms but were instead compound molecules of two or more atoms. Thus Avogadro was able to overcome the difficulty that Dalton and others had encountered when Gay-Lussac reported that above 100 °C the volume of water vapor was twice the volume of the oxygen used to form it. According to Avogadro, the molecule of oxygen had split into two atoms in the course of forming water vapor.

Avogadro's hypothesis was neglected for half a century after it was first published. Many reasons for this neglect have been cited, including some theoretical problems, such as Jöns Jacob Berzelius's "dualism", which asserted that compounds are held together by the attraction of positive and negative electrical charges, making it inconceivable that a molecule composed of two electrically similar atoms—as in oxygen—could exist. An additional barrier to acceptance was the fact that many chemists were reluctant to adopt physical methods (such as vapour-density determinations) to solve their problems. By mid-century, however, some leading figures had begun to view the chaotic multiplicity of competing systems of atomic weights and molecular formulas as intolerable. Moreover, purely chemical evidence began to mount that suggested Avogadro's approach might be right after all. During the 1850s, younger chemists, such as Alexander Williamson in England, Charles Gerhardt and Charles-Adolphe Wurtz in France, and August Kekulé in Germany, began to advocate reforming theoretical chemistry to make it consistent with Avogadrian theory.

Wöhler and the vitalism debate

In 1825, Friedrich Wöhler and Justus von Liebig performed the first confirmed discovery and explanation of isomers, earlier named by Berzelius. Working with cyanic acid and fulminic acid, they correctly deduced that isomerism was caused by differing arrangements of atoms within a molecular structure. In 1827, William Prout classified biomolecules into their modern groupings: carbohydrates, proteins and lipids. After the nature of combustion was settled, a dispute about vitalism and the essential distinction between organic and inorganic substances began. The vitalism question was revolutionized in 1828 when Friedrich Wöhler synthesized urea, thereby establishing that organic compounds could be produced from inorganic starting materials and disproving the theory of vitalism.

This opened a new research field in chemistry, and by the end of the 19th century, scientists were able to synthesize hundreds of organic compounds. The most important among them are mauve, magenta, and other synthetic dyes, as well as the widely used drug aspirin. The discovery of the artificial synthesis of urea contributed greatly to the theory of isomerism, as the empirical chemical formulas for urea and ammonium cyanate are identical (see Wöhler synthesis). In 1832, Friedrich Wöhler and Justus von Liebig discovered and explained functional groups and radicals in relation to organic chemistry, as well as first synthesizing benzaldehyde. Liebig, a German chemist, made major contributions to agricultural and biological chemistry, and worked on the organization of organic chemistry. Liebig is considered the "father of the fertilizer industry" for his discovery of nitrogen as an essential plant nutrient, and his formulation of the Law of the Minimum which described the effect of individual nutrients on crops.

Mid-1800s

In 1840, Germain Hess proposed Hess's law, an early statement of the law of conservation of energy, which establishes that energy changes in a chemical process depend only on the states of the starting and product materials and not on the specific pathway taken between the two states. In 1847, Hermann Kolbe obtained acetic acid from completely inorganic sources, further disproving vitalism. In 1848, William Thomson, 1st Baron Kelvin (commonly known as Lord Kelvin) established the concept of absolute zero, the temperature at which all molecular motion ceases. In 1849, Louis Pasteur discovered that the racemic form of tartaric acid is a mixture of the levorotatory and dextrotatory forms, thus clarifying the nature of optical rotation and advancing the field of stereochemistry. In 1852, August Beer proposed Beer's law, which explains the relationship between the composition of a mixture and the amount of light it will absorb. Based partly on earlier work by Pierre Bouguer and Johann Heinrich Lambert, it established the analytical technique known as spectrophotometry. In 1855, Benjamin Silliman, Jr. pioneered methods of petroleum cracking, which made the entire modern petrochemical industry possible.

Avogadro's hypothesis began to gain broad appeal among chemists only after his compatriot and fellow scientist Stanislao Cannizzaro demonstrated its value in 1858, two years after Avogadro's death. Cannizzaro's chemical interests had originally centered on natural products and on reactions of aromatic compounds; in 1853 he discovered that when benzaldehyde is treated with concentrated base, both benzoic acid and benzyl alcohol are produced—a phenomenon known today as the Cannizzaro reaction. In his 1858 pamphlet, Cannizzaro showed that a complete return to the ideas of Avogadro could be used to construct a consistent and robust theoretical structure that fit nearly all of the available empirical evidence. For instance, he pointed to evidence that suggested that not all elementary gases consist of two atoms per molecule—some were monatomic, most were diatomic, and a few were even more complex.

Another point of contention had been the formulas for compounds of the alkali metals (such as sodium) and the alkaline earth metals (such as calcium), which, in view of their striking chemical analogies, most chemists had wanted to assign to the same formula type. Cannizzaro argued that placing these metals in different categories had the beneficial result of eliminating certain anomalies when using their physical properties to deduce atomic weights. Unfortunately, Cannizzaro's pamphlet was published initially only in Italian and had little immediate impact. The real breakthrough came with an international chemical congress held in the German town of Karlsruhe in September 1860, at which most of the leading European chemists were present. The Karlsruhe Congress had been arranged by Kekulé, Wurtz, and a few others who shared Cannizzaro's sense of the direction chemistry should go. Speaking in French (as everyone there did), Cannizzaro's eloquence and logic made an indelible impression on the assembled body. Moreover, his friend Angelo Pavesi distributed Cannizzaro's pamphlet to attendees at the end of the meeting; more than one chemist later wrote of the decisive impression the reading of this document provided. For instance, Lothar Meyer later wrote that on reading Cannizzaro's paper, "The scales seemed to fall from my eyes." Cannizzaro thus played a crucial role in winning the battle for reform. The system advocated by him, and soon thereafter adopted by most leading chemists, is substantially identical to what is still used today.

Perkin, Crookes, and Nobel

In 1856, Sir William Henry Perkin, age 18, given a challenge by his professor, August Wilhelm von Hofmann, sought to synthesize quinine, the anti-malaria drug, from coal tar. In one attempt, Perkin oxidized aniline using potassium dichromate, whose toluidine impurities reacted with the aniline and yielded a black solid—suggesting a "failed" organic synthesis. Cleaning the flask with alcohol, Perkin noticed purple portions of the solution: a byproduct of the attempt was the first synthetic dye, known as mauveine or Perkin's mauve. Perkin's discovery is the foundation of the dye synthesis industry, one of the earliest successful chemical industries.

German chemist August Kekulé von Stradonitz's most important single contribution was his structural theory of organic composition, outlined in two articles published in 1857 and 1858 and treated in great detail in the pages of his extraordinarily popular *Lehrbuch der organischen Chemie* ("Textbook of Organic Chemistry"), the first installment of which appeared in 1859 and gradually extended to four volumes. Kekulé argued that tetravalent carbon atoms - that is, carbon forming exactly four chemical bonds - could link together to form what he called a "carbon chain" or a "carbon skeleton," to which other atoms with other valences (such as hydrogen, oxygen, nitrogen, and chlorine) could join. He was convinced that it was possible for the chemist to specify this detailed molecular architecture for at least the simpler organic compounds known in his day. Kekulé was not the only chemist to make such claims in this era. The Scottish chemist Archibald Scott Couper published a substantially similar theory nearly simultaneously, and the Russian chemist

Aleksandr Butlerov did much to clarify and expand structure theory. However, it was predominantly Kekulé's ideas that prevailed in the chemical community.

British chemist and physicist William Crookes is noted for his cathode ray studies, fundamental in the development of atomic physics. His researches on electrical discharges through a rarefied gas led him to observe the dark space around the cathode, now called the Crookes dark space. He demonstrated that cathode rays travel in straight lines and produce phosphorescence and heat when they strike certain materials. A pioneer of vacuum tubes, Crookes invented the Crookes tube - an early experimental discharge tube, with partial vacuum with which he studied the behavior of cathode rays. With the introduction of spectrum analysis by Robert Bunsen and Gustav Kirchhoff (1859-1860), Crookes applied the new technique to the study of selenium compounds. Bunsen and Kirchhoff had previously used spectroscopy as a means of chemical analysis to discover caesium and rubidium. In 1861, Crookes used this process to discover thallium in some seleniferous deposits. He continued work on that new element, isolated it, studied its properties, and in 1873 determined its atomic weight. During his studies of thallium, Crookes discovered the principle of the Crookes radiometer, a device that converts light radiation into rotary motion. The principle of this radiometer has found numerous applications in the development of sensitive measuring instruments.

In 1862, Alexander Parkes exhibited Parkesine, one of the earliest synthetic polymers, at the International Exhibition in London. This discovery formed the foundation of the modern plastics industry. In 1864, Cato Maximilian Guldberg and Peter

Waage, building on Claude Louis Berthollet's ideas, proposed the law of mass action. In 1865, Johann Josef Loschmidt determined the exact number of molecules in a mole, later named Avogadro's number.

In 1865, August Kekulé, based partially on the work of Loschmidt and others, established the structure of benzene as a six carbon ring with alternating single and double bonds. Kekulé's novel proposal for benzene's cyclic structure was much contested but was never replaced by a superior theory. This theory provided the scientific basis for the dramatic expansion of the German chemical industry in the last third of the 19th century. Today, the large majority of known organic compounds are aromatic, and all of them contain at least one hexagonal benzene ring of the sort that Kekulé advocated. Kekulé is also famous for having clarified the nature of aromatic compounds, which are compounds based on the benzene molecule. In 1865, Adolf von Baeyer began work on indigo dye, a milestone in modern industrial organic chemistry which revolutionized the dye industry.

Swedish chemist and inventor Alfred Nobel found that when nitroglycerin was incorporated in an absorbent inert substance like *kieselguhr* (diatomaceous earth) it became safer and more convenient to handle, and this mixture he patented in 1867 as dynamite. Nobel later on combined nitroglycerin with various nitrocellulose compounds, similar to collodion, but settled on a more efficient recipe combining another nitrate explosive, and obtained a transparent, jelly-like substance, which was a more powerful explosive than dynamite. Gelignite, or blasting gelatin, as it was named, was patented in 1876; and was followed by a host of similar combinations, modified by the addition of potassium nitrate and various other substances.

Mendeleev's periodic table

An important breakthrough in making sense of the list of known chemical elements (as well as in understanding the internal structure of atoms) was Dmitri Mendeleev's development of the first modern periodic table, or the periodic classification of the elements. Mendeleev, a Russian chemist, felt that there was some type of order to the elements and he spent more than thirteen years of his life collecting data and assembling the concept, initially with the idea of resolving some of the disorder in the field for his students. Mendeleev found that, when all the known chemical elements were arranged in order of increasing atomic weight, the resulting table displayed a recurring pattern, or periodicity, of properties within groups of elements. Mendeleev's law allowed him to build up a systematic periodic table of all the 66 elements then known based on atomic mass, which he published in *Principles of Chemistry* in 1869. His first Periodic Table was compiled on the basis of arranging the elements in ascending order of atomic weight and grouping them by similarity of properties.

Mendeleev had such faith in the validity of the periodic law that he proposed changes to the generally accepted values for the atomic weight of a few elements and, in his version of the periodic table of 1871, predicted the locations within the table of unknown elements together with their properties. He even predicted the likely properties of three yet-to-be-discovered elements, which he called ekaboron (Eb), ekaaluminium (Ea), and ekasilicon (Es), which proved to be good predictors of the properties of scandium, gallium, and germanium, respectively, which each fill the spot in the periodic table assigned by Mendeleev.

At first the periodic system did not raise interest among chemists. However, with the discovery of the predicted elements, notably gallium in 1875, scandium in 1879, and germanium in 1886, it began to win wide acceptance. The subsequent proof of many of his predictions within his lifetime brought fame to Mendeleev as the founder of the periodic law. This organization surpassed earlier attempts at classification by Alexandre-Émile Béguyer de Chancourtois, who published the telluric helix, an early, three-dimensional version of the periodic table of the elements in 1862, John Newlands, who proposed the law of octaves (a precursor to the periodic law) in 1864, and Lothar Meyer, who developed an early version of the periodic table with 28 elements organized by valence in 1864. Mendeleev's table did not include any of the noble gases, however, which had not yet been discovered. Gradually the periodic law and table became the framework for a great part of chemical theory. By the time Mendeleev died in 1907, he enjoyed international recognition and had received distinctions and awards from many countries.

In 1873, Jacobus Henricus van 't Hoff and Joseph Achille Le Bel, working independently, developed a model of chemical bonding that explained the chirality experiments of Pasteur and provided a physical cause for optical activity in chiral compounds. van 't Hoff's publication, called V*oorstel tot Uitbreiding der Tegenwoordige in de Scheikunde gebruikte Structuurformules in de Ruimte*, etc. (Proposal for the development of 3-dimensional chemical structural formulae) and consisting of twelve pages of text and one page of diagrams, gave the impetus to the development of stereochemistry. The concept of the "asymmetrical carbon atom", dealt with in this publication, supplied an explanation of the occurrence of numerous isomers, inexplicable by means of the then current structural formulae. At the same time he pointed out the existence of relationship between optical activity and the presence of an asymmetrical carbon atom.

Josiah Willard Gibbs

American mathematical physicist J. Willard Gibbs's work on the applications of thermodynamics was instrumental in transforming physical chemistry into a rigorous deductive science. During the years from 1876 to 1878, Gibbs worked on the principles of thermodynamics, applying them to the complex processes involved in chemical reactions. He discovered the concept of chemical potential, or the "fuel" that makes chemical reactions work. In 1876 he published his most famous contribution, "On the Equilibrium of Heterogeneous Substances", a compilation of his work on thermodynamics and physical chemistry which laid out the concept of free energy to explain the physical basis of chemical equilibria. In these essays were the beginnings of Gibbs' theories of phases of matter: he considered each state of matter a phase, and each substance a component. Gibbs took all of the variables involved in a chemical reaction - temperature, pressure, energy, volume, and entropy - and included them in one simple equation known as Gibbs' phase rule. Within this paper was perhaps his most outstanding contribution, the introduction of the concept of free energy, now universally called Gibbs free energy in his honor. The Gibbs free energy relates the tendency of a physical or chemical system to simultaneously lower its energy and increase its disorder, or entropy, in a spontaneous natural process. Gibbs's approach allows a researcher to calculate the change in free energy in the process, such as in a chemical reaction, and how fast it will happen. Since virtually all chemical processes and many physical ones involve such changes, his work has significantly impacted both the theoretical and experiential aspects of these sciences. In 1877, Ludwig Boltzmann established statistical derivations of many important physical and chemical concepts, including entropy, and distributions of molecular velocities in the gas phase. Together with Boltzmann and James Clerk Maxwell, Gibbs created a new branch of theoretical physics called statistical mechanics (a term that he coined), explaining the laws of thermodynamics as consequences of the statistical properties of large ensembles of particles. Gibbs also worked on the application of Maxwell's equations to problems in physical optics. Gibbs's derivation of the phenomenological laws of thermodynamics from the statistical properties of systems with many particles was presented in his highly influential textbook *Elementary Principles in Statistical Mechanics*, published in 1902, a year before his death. In that work, Gibbs reviewed the relationship between the laws of thermodynamics and statistical theory of molecular motions. The overshooting of the original function by partial sums of Fourier series at points of discontinuity is known as the Gibbs phenomenon.

Late 19th century

German engineer Carl von Linde's invention of a continuous process of liquefying gases in large quantities formed a basis for the modern technology of refrigeration and provided both impetus and means for conducting scientific research at low temperatures and very high vacuums. He developed a dimethyl ether refrigerator (1874) and an ammonia refrigerator (1876). Though other refrigeration units had been developed earlier, Linde's were the first to be designed with the aim of precise calculations of efficiency. In 1895 he set up a large-scale plant for the production of liquid air. Six years later he developed a method for separating pure liquid oxygen from liquid air that resulted in widespread industrial conversion to processes utilizing oxygen (e.g., in steel manufacture).

In 1883, Svante Arrhenius developed an ion theory to explain conductivity in electrolytes. In 1884, Jacobus Henricus van 't Hoff published *Études de Dynamique chimique* (Studies in Dynamic Chemistry), a seminal study on chemical kinetics. In this work, van 't Hoff entered for the first time the field of physical chemistry. Of great importance was his development of the general thermodynamic relationship between the heat of conversion and the displacement of the equilibrium as a result of temperature variation. At constant volume, the equilibrium in a system will tend to shift in such a direction as to oppose the temperature change which is imposed upon the system. Thus, lowering the temperature results in heat development while increasing the temperature results in heat absorption. This principle of mobile equilibrium was subsequently (1885) put in a general form by Henry Louis Le Chatelier, who extended the principle to include compensation, by change of volume, for imposed pressure changes. The van 't Hoff-Le Chatelier principle, or simply Le Chatelier's principle, explains the response of dynamic chemical equilibria to external stresses.

In 1884, Hermann Emil Fischer proposed the structure of purine, a key structure in many biomolecules, which he later synthesized in 1898. He also began work on the chemistry of glucose and related sugars. In 1885, Eugene Goldstein named the cathode ray, later discovered to be composed of electrons, and the canal ray, later discovered to be positive hydrogen ions that had been stripped of their electrons in a cathode ray tube; these would later be named protons. The year 1885 also saw the publishing of J. H. van 't Hoff's *L'Équilibre chimique dans les Systèmes gazeux ou dissous à I'État dilué* (Chemical equilibria in gaseous systems or strongly diluted solutions), which dealt with this theory of dilute solutions. Here he demonstrated that the "osmotic pressure" in solutions which are sufficiently dilute is proportionate to the concentration and the absolute temperature so that this pressure can be represented by a formula which only deviates from the formula for gas pressure by a coefficient **i**. He also determined the value of *i* by various methods, for example by means of the vapor pressure and François-Marie Raoult's results on the lowering of the freezing point. Thus van 't Hoff was able to prove that thermodynamic laws are not only valid for gases, but also for dilute solutions. His pressure laws, given general validity by the electrolytic dissociation theory of Arrhenius (1884-1887) - the first foreigner who came to work with him in Amsterdam (1888) - are considered the most comprehensive and important in the realm of natural sciences. In 1893, Alfred Werner discovered the octahedral structure of cobalt complexes, thus establishing the field of coordination chemistry.

Ramsay's discovery of the noble gases

- The most celebrated discoveries of Scottish chemist William Ramsay were made in inorganic chemistry. Ramsay was intrigued by the British physicist John Strutt, 3rd Baron Rayleigh's 1892 discovery that the atomic weight of nitrogen found in chemical compounds was lower than that of nitrogen found in the atmosphere. He ascribed this discrepancy to a light gas included in chemical compounds of nitrogen, while Ramsay suspected a hitherto undiscovered heavy gas in atmospheric nitrogen. Using two different methods to remove all known gases from air, Ramsay and Lord Rayleigh were able to announce in 1894 that they had found a monatomic, chemically inert gaseous element that constituted nearly 1 percent of the atmosphere; they named it argon.

The following year, Ramsay liberated another inert gas from a mineral called cleveite; this proved to be helium, previously known only in the solar spectrum. In his book *The Gases of the Atmosphere* (1896), Ramsay showed that the positions of helium and argon in the periodic table of elements indicated that at least three more noble gases might exist. In 1898 Ramsay and the British chemist Morris W. Travers isolated these elements—called neon, krypton, and xenon—from air brought to a liquid state at low temperature and high pressure. Sir William Ramsay worked with Frederick Soddy to demonstrate, in 1903, that alpha particles (helium nuclei) were continually produced during the radioactive decay of a sample of radium. Ramsay was awarded the 1904 Nobel Prize for Chemistry in recognition of "services in the discovery of the inert gaseous elements in air, and his determination of their place in the periodic system."

In 1897, J. J. Thomson discovered the electron using the cathode ray tube. In 1898, Wilhelm Wien demonstrated that canal rays (streams of positive ions) can be deflected by magnetic fields, and that the amount of deflection is proportional to the mass-to-charge ratio. This discovery would lead to the analytical technique known as mass spectrometry in 1912.

Marie and Pierre Curie

- Marie Skłodowska-Curie was a Polish-born French physicist and chemist who is famous for her pioneering research on radioactivity. She and her husband are considered to have laid the cornerstone of the nuclear age with their research on radioactivity. Marie was fascinated with the work of Henri Becquerel, a French physicist who discovered in 1896 that uranium casts off rays similar to the X-rays discovered by Wilhelm Röntgen. Marie Curie began studying uranium in late 1897 and theorized, according to a 1904 article she wrote for Century magazine, "that the emission of rays by the compounds of uranium is a property of the metal itself—that it is an atomic property of the element uranium independent of its chemical or physical state." Curie took Becquerel's work a few steps

> further, conducting her own experiments on uranium rays. She discovered that the rays remained constant, no matter the condition or form of the uranium. The rays, she theorized, came from the element's atomic structure. This revolutionary idea created the field of atomic physics and the Curies coined the word *radioactivity* to describe the phenomena.

Pierre and Marie further explored radioactivity by working to separate the substances in uranium ores and then using the electrometer to make radiation measurements to ‘trace’ the minute amount of unknown radioactive element among the fractions that resulted. Working with the mineral pitchblende, the pair discovered a new radioactive element in 1898. They named the element polonium, after Marie's native country of Poland. On December 21, 1898, the Curies detected the presence of another radioactive material in the pitchblende. They presented this finding to the French Academy of Sciences on December 26, proposing that the new element be called radium. The Curies then went to work isolating polonium and radium from naturally occurring compounds to prove that they were new elements. In 1902, the Curies announced that they had produced a decigram of pure radium, demonstrating its existence as a unique chemical element. While it took three years for them to isolate radium, they were never able to isolate polonium. Along with the discovery of two new elements and finding techniques for isolating radioactive isotopes, Curie oversaw the world's first studies into the treatment of neoplasms, using radioactive isotopes. With Henri Becquerel and her husband, Pierre Curie, she was awarded the 1903 Nobel Prize for Physics. She was the sole winner of the 1911

Nobel Prize for Chemistry. She was the first woman to win a Nobel Prize, and she is the only woman to win the award in two different fields.

While working with Marie to extract pure substances from ores, an undertaking that really required industrial resources but that they achieved in relatively primitive conditions, Pierre himself concentrated on the physical study (including luminous and chemical effects) of the new radiations. Through the action of magnetic fields on the rays given out by the radium, he proved the existence of particles that were electrically positive, negative, and neutral; these Ernest Rutherford was afterward to call alpha, beta, and gamma rays. Pierre then studied these radiations by calorimetry and also observed the physiological effects of radium, thus opening the way to radium therapy. Among Pierre Curie's discoveries were that ferromagnetic substances exhibited a critical temperature transition, above which the substances lost their ferromagnetic behavior - this is known as the "Curie point." He was elected to the Academy of Sciences (1905), having in 1903 jointly with Marie received the Royal Society's prestigious Davy Medal and jointly with her and Becquerel the Nobel Prize for Physics. He was run over by a carriage in the rue Dauphine in Paris in 1906 and died instantly. His complete works were published in 1908.

Ernest Rutherford

- New Zealand-born chemist and physicist Ernest Rutherford is considered to be "the father of nuclear physics." Rutherford is best known for devising the names alpha, beta, and gamma to classify various forms of radioactive "rays" which were poorly understood at his time (alpha and beta rays are particle beams, while gamma rays are a form of high-energy electromagnetic radiation). Rutherford deflected alpha rays with both electric and magnetic fields in 1903. Working with Frederick Soddy, Rutherford explained that radioactivity is due to the transmutation of elements, now known to involve nuclear reactions.

He also observed that the intensity of radioactivity of a radioactive element decreases over a unique and regular amount of time until a point of stability, and he named the halving time the "half-life." In 1901 and 1902 he worked with Frederick Soddy to prove that atoms of one radioactive element would spontaneously turn into another, by expelling a piece of the atom at high velocity. In 1906 at the University of Manchester, Rutherford oversaw an experiment conducted by his students Hans Geiger (known for the Geiger counter) and Ernest Marsden. In the Geiger–Marsden experiment, a beam of alpha particles, generated by the radioactive decay of radon, was directed normally onto a sheet of very thin gold foil in an evacuated chamber. Under the prevailing plum pudding model, the alpha particles should all have passed through the foil and hit the detector screen, or have been deflected by, at most, a few degrees.

However, the actual results surprised Rutherford. Although many of the alpha particles did pass through as expected, many others were deflected at small angles while others were reflected back to the alpha source. They observed that a very small percentage of particles were deflected through angles much larger than 90 degrees. The gold foil experiment showed large deflections for a small fraction of incident particles. Rutherford realized that, because some of the alpha particles were deflected or reflected, the atom had a concentrated centre of positive charge and of relatively large mass - Rutherford later termed this positive center the "atomic nucleus". The alpha particles had either hit the positive centre directly or passed by it close enough to be affected by its positive charge. Since many other particles passed through the gold foil, the positive centre would have to be a relatively small size compared to the rest of the atom - meaning that the atom is mostly open space. From his results, Rutherford developed a model of the atom that was similar to the solar system, known as the Rutherford model. Like planets, electrons orbited a central, sun-like nucleus. For his work with radiation and the atomic nucleus, Rutherford received the 1908 Nobel Prize in Chemistry.

20th century

- In 1903, Mikhail Tsvet invented chromatography, an important analytic technique. In 1904, Hantaro Nagaoka proposed an early nuclear model of the atom, where electrons orbit a dense massive nucleus. In 1905, Fritz Haber and Carl Bosch developed the Haber process for making ammonia, a milestone in industrial chemistry with deep consequences in agriculture. The Haber process, or Haber-Bosch process, combined nitrogen and hydrogen to form ammonia in industrial quantities for production of fertilizer and munitions. The food production for half the world's current population depends on this method for producing fertilizer. Haber, along with Max Born, proposed the Born–Haber cycle as a method for evaluating the lattice energy of an ionic solid. Haber has also been described as the "father of chemical warfare" for his work developing and deploying chlorine and other poisonous gases during World War I.

In 1905, Albert Einstein explained Brownian motion in a way that definitively proved atomic theory. Leo Baekeland invented bakelite, one of the first commercially successful plastics. In 1909, American physicist Robert Andrews Millikan - who had studied in Europe under Walther Nernst and Max Planck - measured the charge of individual electrons with unprecedented accuracy through the oil drop experiment, in which he measured the electric charges on tiny falling water (and later oil) droplets. His study established that any particular droplet's electrical charge is a multiple of a definite, fundamental value — the electron's charge — and thus a confirmation that all electrons have the same charge and mass. Beginning in 1912, he spent several years investigating and finally proving Albert Einstein's proposed linear relationship between energy and frequency, and providing the first direct photoelectric support for Planck's constant. In 1923 Millikan was awarded the Nobel Prize for Physics.

In 1909, S. P. L. Sørensen invented the pH concept and developed methods for measuring acidity. In 1911, Antonius Van den Broek proposed the idea that the elements on the periodic table are more properly organized by positive nuclear charge rather than atomic weight. In 1911, the first Solvay Conference was held in Brussels, bringing together most of the most prominent scientists of the day. In 1912, William Henry Bragg and William Lawrence Bragg proposed Bragg's law and established the field of X-ray crystallography, an important tool for elucidating the crystal structure of substances. In 1912, Peter Debye used the concept of a molecular dipole to describe asymmetric charge distribution in some molecules.

Niels Bohr

In 1913, Niels Bohr, a Danish physicist, introduced the concepts of quantum mechanics to atomic structure by proposing what is now known as the Bohr model of the atom, where electrons exist only in strictly defined circular orbits around the nucleus similar to rungs on a ladder. The Bohr Model is a planetary model in which the negatively charged electrons orbit a small, positively charged nucleus similar to the planets orbiting the Sun (except that the orbits are not planar) - the gravitational force of the solar system is mathematically akin to the attractive Coulomb (electrical) force between the positively charged nucleus and the negatively charged electrons.

In the Bohr model, however, electrons orbit the nucleus in orbits that have a set size and energy - the energy levels are said to be *quantized*, which means that only certain orbits with certain radii are allowed; orbits in between simply don't exist. The energy of the orbit is related to its size - that is, the lowest energy is found in the smallest orbit. Bohr also postulated that electromagnetic radiation is absorbed or emitted when an electron moves from one orbit to another. Because only certain electron orbits are permitted, the emission of light accompanying a jump of an electron from an excited energy state to ground state produces a unique emission spectrum for each element. Bohr later received the Nobel Prize in physics for this work.

Niels Bohr also worked on the principle of complementarity, which states that an electron can be interpreted in two mutually exclusive and valid ways. Electrons can be interpreted as wave or particle models. His hypothesis was that an incoming particle would strike the nucleus and create an excited compound nucleus. This formed the basis of his liquid drop model and later provided a theory base for nuclear fission after its discovery by chemists Otto Hahn and Fritz Strassman, and explanation and naming by physicists Lise Meitner and Otto Frisch.

In 1913, Henry Moseley, working from Van den Broek's earlier idea, introduced the concept of atomic number to fix some inadequacies of Mendeleev's periodic table, which had been based on atomic weight. The peak of Frederick Soddy's career in radiochemistry was in 1913 with his formulation of the concept of isotopes, which stated that certain elements exist in two or more forms which have different atomic weights but which are indistinguishable chemically. He is remembered for proving the existence of isotopes of certain radioactive elements, and is also credited, along with others, with the discovery of the element protactinium in 1917. In 1913, J. J. Thomson expanded on the work of Wien by showing that charged subatomic particles can be separated by their mass-to-charge ratio, a technique known as mass spectrometry.

Gilbert N. Lewis

American physical chemist Gilbert N. Lewis laid the foundation of valence bond theory; he was instrumental in developing a bonding theory based on the number of electrons in the outermost "valence" shell of the atom. In 1902, while Lewis was trying to explain valence to his students, he depicted atoms as constructed of a concentric series of cubes with electrons at each corner. This "cubic atom" explained the eight groups in the periodic table and represented his idea that chemical bonds are formed by electron transference to give each atom a complete set of eight outer electrons (an "octet").

Lewis's theory of chemical bonding continued to evolve and, in 1916, he published his seminal article "The Atom of the Molecule", which suggested that a chemical bond is a pair of electrons shared by two atoms. Lewis's model equated the classical chemical bond with the sharing of a pair of electrons between the two bonded atoms. Lewis introduced the "electron dot diagrams" in this paper to symbolize the electronic structures of atoms and molecules. Now known as Lewis structures, they are discussed in virtually every introductory chemistry book.

Shortly after the publication of his 1916 paper, Lewis became involved with military research. He did not return to the subject of chemical bonding until 1923, when he masterfully summarized his model in a short monograph entitled Valence and the Structure of Atoms and Molecules. His renewal of interest in this subject was largely stimulated by the activities of the American chemist and General Electric researcher Irving Langmuir, who between 1919 and 1921 popularized and elaborated Lewis's model. Langmuir subsequently introduced the term *covalent bond*. In 1921, Otto Stern and Walther Gerlach established the concept of quantum mechanical spin in subatomic particles.

For cases where no sharing was involved, Lewis in 1923 developed the electron pair theory of acids and base: Lewis redefined an acid as any atom or molecule with an incomplete octet that was thus capable of accepting electrons from another atom; bases were, of course, electron donors. His theory is known as the concept of Lewis acids and bases. In 1923, G. N. Lewis and Merle Randall published *Thermodynamics and the Free Energy of Chemical Substances*, first modern treatise on chemical thermodynamics.

The 1920s saw a rapid adoption and application of Lewis's model of the electron-pair bond in the fields of organic and coordination chemistry. In organic chemistry, this was primarily due to the efforts of the British chemists Arthur Lapworth, Robert Robinson, Thomas Lowry, and Christopher Ingold; while in coordination chemistry, Lewis's bonding model was promoted through the efforts of the American chemist Maurice Huggins and the British chemist Nevil Sidgwick.

Quantum mechanics

In 1924, French quantum physicist Louis de Broglie published his thesis, in which he introduced a revolutionary theory of electron waves based on wave–particle duality. In his time, the wave and particle interpretations of light and matter were seen as being at odds with one another, but de Broglie suggested that these seemingly different characteristics were instead the same behavior observed from different perspectives — that particles can behave like waves, and waves (radiation) can behave like particles. Broglie's proposal offered an explanation of the restricted motion of electrons within the atom. The first publications of Broglie's idea of "matter waves" had drawn little attention from other physicists, but a copy of his doctoral thesis chanced to reach Einstein, whose response was enthusiastic. Einstein stressed the importance of Broglie's work both explicitly and by building further on it.

In 1925, Austrian-born physicist Wolfgang Pauli developed the Pauli exclusion principle, which states that no two electrons around a single nucleus in an atom can occupy the same quantum state simultaneously, as described by four quantum numbers. Pauli made major contributions to quantum mechanics and quantum field theory - he was awarded the 1945 Nobel Prize for Physics for his discovery of the Pauli exclusion principle - as well as solid-state physics, and he successfully hypothesized the existence of the neutrino. In addition to his original work, he wrote masterful syntheses of several areas of physical theory that are considered classics of scientific literature.

In 1926 at the age of 39, Austrian theoretical physicist Erwin Schrödinger produced the papers that gave the foundations of quantum wave mechanics. In those papers he described his partial differential equation that is the basic equation of quantum mechanics and bears the same relation to the mechanics of the atom as Newton's equations of motion bear to planetary astronomy. Adopting a proposal made by Louis de Broglie in 1924 that particles of matter have a dual nature and in some situations act like waves, Schrödinger introduced a theory describing the behaviour of such a system by a wave equation that is now known as the Schrödinger equation. The solutions to Schrödinger's equation, unlike the solutions to Newton's equations, are wave functions that can only be related to the probable occurrence of physical events. The readily visualized sequence of events of the planetary orbits of Newton is, in quantum mechanics, replaced by the more abstract notion of probability. (This aspect of the quantum theory made Schrödinger and several other physicists profoundly unhappy, and he devoted much of his later life to formulating philosophical objections to the generally accepted interpretation of the theory that he had done so much to create.)

German theoretical physicist Werner Heisenberg was one of the key creators of quantum mechanics. In 1925, Heisenberg discovered a way to formulate quantum mechanics in terms of matrices. For that discovery, he was awarded the Nobel Prize for Physics for 1932. In 1927 he published his uncertainty principle, upon which he built his philosophy and for which he is best known. Heisenberg was able to demonstrate that if you were studying an electron in an atom you could say where it was (the electron's location) or where it was going (the electron's velocity), but it was impossible to express both at the same time. He also made important contributions to the theories of the hydrodynamics of turbulent flows, the atomic nucleus, ferromagnetism, cosmic rays, and subatomic particles, and he was instrumental in planning the first West German nuclear reactor at Karlsruhe, together with a research reactor in Munich, in 1957. Considerable controversy surrounds his work on atomic research during World War II.

Quantum chemistry

Some view the birth of quantum chemistry in the discovery of the Schrödinger equation and its application to the hydrogen atom in 1926. However, the 1927 article of Walter Heitler and Fritz London is often recognised as the first milestone in the history of quantum chemistry. This is the first application of quantum mechanics to the diatomic hydrogen molecule, and thus to the phenomenon of the chemical bond. In the following years much progress was accomplished by Edward Teller, Robert S. Mulliken, Max Born, J. Robert Oppenheimer, Linus Pauling, Erich Hückel, Douglas Hartree and Vladimir Aleksandrovich Fock, to cite a few.

Still, skepticism remained as to the general power of quantum mechanics applied to complex chemical systems. The situation around 1930 is described by Paul Dirac:

The underlying physical laws necessary for the mathematical theory of a large part of physics and the whole of chemistry are thus completely known, and the difficulty is only that the exact application of these laws leads to equations much too complicated to be soluble. It therefore becomes desirable that approximate practical methods of applying quantum mechanics should be developed, which can lead to an explanation of the main features of complex atomic systems without too much computation.

Hence the quantum mechanical methods developed in the 1930s and 1940s are often referred to as theoretical molecular or atomic physics to underline the fact that they were more the application of quantum mechanics to chemistry and spectroscopy than answers to chemically relevant questions. In 1951, a milestone article in quantum chemistry is the seminal paper of Clemens C. J. Roothaan on Roothaan equations. It opened the avenue to the solution of the self-consistent field equations for small molecules like hydrogen or nitrogen. Those computations were performed with the help of tables of integrals which were computed on the most advanced computers of the time.

In the 1940s many physicists turned from molecular or atomic physics to nuclear physics (like J. Robert Oppenheimer or Edward Teller). Glenn T. Seaborg was an American nuclear chemist best known for his work on isolating and identifying transuranium elements (those heavier than uranium). He shared the 1951 Nobel Prize for Chemistry with Edwin Mattison McMillan for their independent discoveries of transuranium elements. Seaborgium was named in his honour, making him the only person, along with Albert Einstein and Yuri Oganessian, for whom a chemical element was named during his lifetime.

Molecular biology and biochemistry

- By the mid 20th century, in principle, the integration of physics and chemistry was extensive, 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. However, though some principles deduced from quantum mechanics were able to predict qualitatively some chemical features for biologically relevant molecules, they were, till the end of the 20th century, more a collection of rules, observations, and recipes than rigorous ab initio quantitative methods.

This heuristic approach triumphed in 1953 when James Watson and Francis Crick deduced the double helical structure of DNA by constructing models constrained by and informed by the knowledge of the chemistry of the constituent parts and the X-ray diffraction patterns obtained by Rosalind Franklin. This discovery lead to an explosion of research into the biochemistry of life.

In the same year, the Miller–Urey experiment demonstrated that basic constituents of protein, simple amino acids, could themselves be built up from simpler molecules in a simulation of primordial processes on Earth. This first attempt by chemists to study hypothetical processes in the laboratory under controlled conditions helped kickstart bountiful research, within the natural sciences, into the origins of life.

In 1983 Kary Mullis devised a method for the in-vitro amplification of DNA, known as the polymerase chain reaction (PCR), which revolutionized the chemical processes used in the laboratory to manipulate it. PCR could be used to synthesize specific pieces of DNA and made possible the sequencing of DNA of organisms, which culminated in the huge human genome project.

An important piece in the double helix puzzle was solved by one of Pauling's students Matthew Meselson and Frank Stahl, the result of their collaboration (Meselson–Stahl experiment) has been called as "the most beautiful experiment in biology".

They used a centrifugation technique that sorted molecules according to differences in weight. Because nitrogen atoms are a component of DNA, they were labelled and therefore tracked in replication in bacteria.

Late 20th century

In 1970, John Pople developed the Gaussian program greatly easing computational chemistry calculations. In 1971, Yves Chauvin offered an explanation of the reaction mechanism of olefin metathesis reactions. In 1975, Karl Barry Sharpless and his group discovered stereoselective oxidation reactions including Sharpless epoxidation, Sharpless asymmetric dihydroxylation, and Sharpless oxyamination. In 1985, Harold Kroto, Robert Curl and Richard Smalley discovered fullerenes, a class of large carbon molecules superficially resembling the geodesic dome designed by architect R. Buckminster Fuller. In 1991, Sumio Iijima used electron microscopy to discover a type of cylindrical fullerene known as a carbon nanotube, though earlier work had been done in the field as early as 1951. This material is an important component in the field of nanotechnology. In 1994, K. C. Nicolaou with his group and Robert A. Holton and his group, achieved the first total synthesis of Taxol. In 1995, Eric Cornell and Carl Wieman produced the first Bose–Einstein condensate, a substance that displays quantum mechanical properties on the macroscopic scale.

Mathematics and chemistry

Classically, before the 20th century, chemistry was defined as the science of the nature of matter and its transformations. It was therefore clearly distinct from physics which was not concerned with such dramatic transformation of matter. Moreover, in contrast to physics, chemistry was not using much of mathematics. Even some were particularly reluctant to use mathematics within chemistry. For example, Auguste Comte wrote in 1830:

Every attempt to employ mathematical methods in the study of chemical questions must be considered profoundly irrational and contrary to the spirit of chemistry.... if mathematical analysis should ever hold a prominent place in chemistry -- an aberration which is happily almost impossible -- it would occasion a rapid and widespread degeneration of that science.

However, in the second part of the 19th century, the situation changed and August Kekulé wrote in 1867:

I rather expect that we shall someday find a mathematico-mechanical explanation for what we now call atoms which will render an account of their properties.

Scope of chemistry

As understanding of the nature of matter has evolved, so too has the self-understanding of the science of chemistry by its practitioners. This continuing historical process of evaluation includes the categories, terms, aims and scope of chemistry. Additionally, the development of the social institutions and networks which support chemical enquiry are highly significant factors that enable the production, dissemination and application of chemical knowledge. (See Philosophy of chemistry)

Chemical industry

- Main article: Chemical industry

The later part of the nineteenth century saw a huge increase in the exploitation of petroleum extracted from the earth for the production of a host of chemicals and largely replaced the use of whale oil, coal tar and naval stores used previously. Large-scale production and refinement of petroleum provided feedstocks for liquid fuels such as gasoline and diesel, solvents, lubricants, asphalt, waxes, and for the production of many of the common materials of the modern world, such as synthetic fibers, plastics, paints, detergents, pharmaceuticals, adhesives and ammonia as fertilizer and for other uses. Many of these required new catalysts and the utilization of chemical engineering for their cost-effective production.

In the mid-twentieth century, control of the electronic structure of semiconductor materials was made precise by the creation of large ingots of extremely pure single crystals of silicon and germanium. Accurate control of their chemical composition by doping with other elements made the production of the solid state transistor in 1951 and made possible the production of tiny integrated circuits for use in electronic devices, especially computers.