HISTORY OF SCIENCE

Volume 4

Benjamin Kent

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History of Science, Volume 4
by Benjamin Kent

www.bibliotex.com

Ebook ISBN: 9781984668691

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History of Science in China

Ancient Chinese scientists and engineers made significant scientific innovations, findings and technological advances across various scientific disciplines including the natural sciences, engineering, medicine, military technology, mathematics, geology and astronomy.

Among the earliest inventions were the abacus, the sundial, and the Kongming lantern. The *Four Great Inventions,*the compass, gunpowder, papermaking, and printing – were among the most important technological advances, only known to Europe by the end of the Middle Ages 1000 years later. The Tang dynasty (AD 618–906) in particular was a time of great innovation. A good deal of exchange occurred between Western and Chinese discoveries up to the Qing dynasty. The Jesuit China missions of the 16th and 17th centuries introduced Western science and astronomy, then undergoing its own revolution, to China, and knowledge of Chinese technology was brought to Europe. In the 19th and 20th centuries the introduction of Western technology was a major factor in the modernization of China. Much of the early Western work in the history of science in China was done by Joseph Needham.

Mo Di and the School of Names

The Warring States period began 2500 years ago at the time of the invention of the crossbow. Needham notes that the invention of the crossbow "far outstripped the progress in defensive armor", which made the wearing of armor useless to the princes and dukes of the states. At this time, there were also many nascent schools of thought in China—the Hundred Schools of Thought, scattered among many polities. The schools served as communities which advised the rulers of these states. Mo Di (Mozi, 470 BCE–c. 391 BCE) introduced concepts useful to one of those rulers, such as defensive fortification. One of these concepts, *fa* (principle or method) was extended by the School of Names (*Ming jia*, *ming*=name), which began a systematic exploration of logic. The development of a school of logic was cut short by the defeat of Mohism's political sponsors by the Qin dynasty, and the subsumption of *fa* as law rather than method by the Legalists (*Fa jia*).

Needham further notes that the Han dynasty, which conquered the short-lived Qin, were made aware of the need for law by Lu Jia and by Shusun Tong, as defined by the scholars, rather than the generals.

You conquered the empire on horseback, but from horseback you will never succeed in ruling it.

- *—Lu Jia*

Derived from Taoist philosophy, one of the newest longstanding contributions of the ancient Chinese are in Traditional Chinese medicine, including acupuncture and herbal medicine. The practice of acupuncture can be traced back as far as the 1st millennium BC and some scientists believe that there is evidence that practices similar to acupuncture were used in Eurasia during the early Bronze Age.

Using shadow clocks and the abacus (both invented in the ancient Near East before spreading to China), the Chinese were able to record observations, documenting the first recorded solar eclipse in 2137 BC, and making the first recording of any planetary grouping in 500 BC. These claims, however, are highly disputed and rely on much supposition. The *Book of Silk* was the first definitive atlas of comets, written *c.* 400 BC. It listed 29 comets (referred to as *sweeping stars*) that appeared over a period of about 300 years, with renderings of comets describing an event its appearance corresponded to.

In architecture, the pinnacle of Chinese technology manifested itself in the Great Wall of China, under the first Chinese Emperor Qin Shi Huang between 220 and 200 BC. Typical Chinese architecture changed little from the succeeding Han dynasty until the 19th century. The Qin dynasty also developed the crossbow, which later became the mainstream weapon in Europe. Several remains of crossbows have been found among the soldiers of the Terracotta Army in the tomb of Qin Shi Huang.

Han dynasty

The Eastern Han dynasty scholar and astronomer Zhang Heng (78–139 AD) invented the first water-powered rotating armillary sphere (the first armillary sphere having been invented by the Greek Eratosthenes), and catalogued 2,500 stars and over 100 constellations. In 132, he invented the first seismological detector, called the "*Houfeng Didong Yi*" ("Instrument for inquiring into the wind and the shaking of the earth"). According to the *History of Later Han Dynasty* (25–220 AD), this seismograph was an urn-like instrument, which would drop one of eight balls to indicate when and in which direction an earthquake had occurred. On June 13, 2005, Chinese seismologists announced that they had created a replica of the instrument.

The mechanical engineer Ma Jun (c. 200–265 AD) was another impressive figure from ancient China. Ma Jun improved the design of the silk loom, designed mechanical chain pumps to irrigate palatial gardens, and created a large and intricate mechanical puppet theatre for Emperor Ming of Wei, which was operated by a large hidden waterwheel. However, Ma Jun's most impressive invention was the south-pointing chariot, a complex mechanical device that acted as a mechanical compass vehicle. It incorporated the use of a differential gear in order to apply equal amount of torque to wheels rotating at different speeds, a device that is found in all modern automobiles.

Sliding calipers were invented in China almost 2,000 years ago. The Chinese civilization was the earliest civilization to experiment successfully with aviation, with the kite and Kongming lantern (proto Hot air balloon) being the first flying machines.

"Four Great Inventions"

The "Four Great Inventions" (simplified Chinese: traditional Chinese: pinyin: *sì dà fāmíng*) are the compass, gunpowder, papermaking and printing. Paper and printing were developed first. Printing was recorded in China in the Tang Dynasty, although the earliest surviving examples of printed cloth patterns date to before 220. Pin-pointing the development of the compass can be difficult: the magnetic attraction of a needle is attested by the *Louen-heng*, composed between AD 20 and 100, although the first undisputed magnetized needles in Chinese literature appear in 1086.

By AD 300, Ge Hong, an alchemist of the Jin dynasty, conclusively recorded the chemical reactions caused when saltpetre, pine resin and charcoal were heated together, in *Book of the Master of the Preservations of Solidarity*. Another early record of gunpowder, a Chinese book from *c*. 850 AD, indicates:

"Some have heated together sulfur, realgar and saltpeter with honey; smoke and flames result, so that their hands and faces have been burnt, and even the whole house where they were working burned down."

These four discoveries had an enormous impact on the development of Chinese civilization and a far-ranging global impact. Gunpowder, for example, spread to the Arabs in the 13th century and thence to Europe. According to English philosopher Francis Bacon, writing in *Novum Organum*:

Printing, gunpowder and the compass: These three have changed the whole face and state of things throughout the world; the first in literature, the second in warfare, the third in navigation; whence have followed innumerable changes, in so much that no empire, no sect, no star seems to have exerted greater power and influence in human affairs than these mechanical discoveries.

One of the most important military treatises of all Chinese history was the *Huo Long Jing* written by Jiao Yu in the 14th century. For gunpowder weapons, it outlined the use of fire arrows and rockets, fire lances and firearms, land mines and naval mines, bombards and cannons, two stage rockets, along with different compositions of gunpowder, including 'magic gunpowder', 'poisonous gunpowder', and 'blinding and burning gunpowder' (refer to his article).

For the 11th century invention of ceramic movable type printing by Bi Sheng (990–1051), it was enhanced by the wooden movable type of Wang Zhen in 1298 and the bronze metal movable type of Hua Sui in 1490.

China's scientific revolution

Among the engineering accomplishments of early China were matches, dry docks, the double-action piston pump, cast iron, the iron plough, the horse collar, the multi-tube seed drill, the wheelbarrow, the suspension bridge, the parachute, natural gas as fuel, the raised-relief map, the propeller, the sluice gate, and the pound lock. The Tang dynasty (AD 618–907) and Song dynasty (AD 960–1279) in particular were periods of great innovation.

In the 7th century, book-printing was developed in China, Korea and Japan, using delicate hand-carved wooden blocks to print individual pages. The 9th century *Diamond Sutra* is the earliest known printed document. Movable type was also used in China for a time, but was abandoned because of the number of characters needed; it would not be until Johannes

Gutenberg that the technique was reinvented in a suitable environment.

In addition to gunpowder, the Chinese also developed improved delivery systems for the Byzantine weapon of Greek fire, Meng Huo You and Pen Huo Qi first used in China *c.* 900. Chinese illustrations were more realistic than in Byzantine manuscripts, and detailed accounts from 1044 recommending its use on city walls and ramparts show the brass container as fitted with a horizontal pump, and a nozzle of small diameter. The records of a battle on the Yangtze near Nanjing in 975 offer an insight into the dangers of the weapon, as a change of wind direction blew the fire back onto the Song forces.

Song Dynasty

The Song dynasty (960–1279) brought a new stability for China after a century of civil war, and started a new area of modernisation by encouraging examinations and meritocracy. The first Song Emperor created political institutions that allowed a great deal of freedom of discourse and thought, which facilitated the growth of scientific advance, economic reforms, and achievements in arts and literature. Trade flourished both within China and overseas, and the encouragement of technology allowed the mints at Kaifeng and Hangzhou to gradually increase in production. In 1080, the mints of Emperor Shenzong had produced 5 billion coins (roughly 50 per Chinese citizen), and the first banknotes were produced in 1023. These coins were so durable that they would still be in use 700 years later, in the 18th century.

There were many famous inventors and early scientists in the Song Dynasty period. The statesman Shen Kuo is best known for his book known as the *Dream Pool Essays* (1088 AD). In it, he wrote of use for a drydock to repair boats, the navigational magnetic compass, and the discovery of the concept of true north (with magnetic declination towards the North Pole). Shen Kuo also devised a geological theory for land formation, or geomorphology, and theorized that there was climate change in geological regions over an enormous span of time.

The equally talented statesman Su Song was best known for his engineering project of the Astronomical Clock Tower of Kaifeng, by 1088 AD. The clock tower was driven by a rotating waterwheel and escapement mechanism. Crowning the top of the clock tower was the large bronze, mechanically-driven, rotating armillary sphere. In 1070, Su Song also compiled the *Ben Cao Tu Jing* (Illustrated Pharmacopoeia, original source material from 1058 to 1061 AD) with a team of scholars. This pharmaceutical treatise covered a wide range of other related subjects, including botany, zoology, mineralogy, and metallurgy.

Chinese astronomers were the first to record observations of a supernova, the first being the SN 185, recorded during the Han dynasty. Chinese astronomers made two more notable supernova observations during the Song Dynasty: the SN 1006, the brightest recorded supernova in history; and the SN 1054, making the Crab Nebula the first astronomical object recognized as being connected to a supernova explosion.

Archaeology

During the early half of the Song dynasty (960–1279), the study of archaeology developed out of the antiquarian interests of the educated gentry and their desire to revive the use of ancient vessels in state rituals and ceremonies. This and the belief that ancient vessels were products of 'sages' and not common people was criticized by Shen Kuo, who took an interdisciplinary approach to archaeology, incorporating his archaeological findings into studies on metallurgy, optics, astronomy, geometry, and ancient music measures. His contemporary Ouyang Xiu (1007–1072) compiled an analytical catalogue of ancient rubbings on stone and bronze, which Patricia B. Ebrey says pioneered ideas in early epigraphy and archaeology. In accordance with the beliefs of the later Leopold von Ranke (1795–1886), some Song gentry—such as Zhao Mingcheng (1081–1129)—supported the primacy of contemporaneous archaeological finds of ancient inscriptions over historical works written after the fact, which they contested to be unreliable in regard to the former evidence. Hong Mai (1123–1202) used ancient Han Dynasty era vessels to debunk what he found to be fallacious descriptions of Han vessels in the *Bogutu* archaeological catalogue compiled during the latter half of Huizong's reign (1100–1125).

Geology and climatology

In addition to his studies in meteorology, astronomy, and archaeology mentioned above, Shen Kuo also made hypotheses in regards to geology and climatology in his *Dream Pool Essays* of 1088, specifically his claims regarding geomorphology and climate change. Shen believed that land was reshaped over time due to perpetual erosion, uplift, and deposition of silt, and cited his observance of horizontal strata of fossils embedded in a cliffside at Taihang as evidence that the area was once the location of an ancient seashore that had shifted hundreds of miles east over an enormous span of time. Shen also wrote that since petrified bamboos were found underground in a dry northern climate zone where they had never been known to grow, climates naturally shifted geographically over time.

Chemistry

Until the Song Dynasty, Chinese medicine classified drugs under the system of the *Zhenghe bencao* (Herbal of the Zhenghe Era):

- Superior drugs, associated with immortality, were used for the realization of vital powers
- Medium drugs that enrich one's nature
- Inferior drugs were those used to treat diseases

These early forms of drugs were made using primitive methods, usually just simple dried herbs, or unprocessed minerals. They were developed into combinations known as "elixirs of immortality". These early magical practices, supported by the imperial courts of Shihunagdi (259-210 BCE) and Emperor Wu (156-87 BCE) eventually led to the first observations of chemistry in ancient China. Chinese alchemists searched for ways to make cinnabar, gold and other minerals water soluble so they could be ingested, such as using a solution of potassium nitrate in vinegar . Solubilzation of cinnabar was found to occur only if an impurity (chloride ion) was present. Gold also was soluble when iodate was present in crude niter deposits.

Mongol transmission

Mongol rule under the Yuan dynasty saw technological advances from an economic perspective, with the first mass production of paper banknotes by Kublai Khan in the 13th century. Numerous contacts between Europe and the Mongols occurred in the 13th century, particularly through the unstable Franco-Mongol alliance. Chinese corps, expert in siege warfare, formed an integral part of the Mongol armies campaigning in the West. In 1259–1260 military alliance of the Franks knights of the ruler of Antioch, Bohemond VI and his father-in-law Hetoum I with the Mongols under Hulagu, in which they fought together for the conquests of Muslim Syria, taking together the city of Aleppo, and later Damascus. William of Rubruck, an ambassador to the Mongols in 1254–1255, a personal friend of Roger Bacon, is also often designated as a possible intermediary in the transmission of gunpowder know-how between the East and the West. The compass is often said to have been introduced by the Master of the Knights Templar Pierre de Montaigu between 1219 and 1223, from one of his travels to visit the Mongols in Persia.

Chinese and Arabic astronomy intermingled under Mongol rule. Muslim astronomers worked in the Chinese Astronomical Bureau established by Kublai Khan, while some Chinese astronomers also worked at the Persian Maragha observatory.

Before this, in ancient times, Indian astronomers had lent their expertise to the Chinese court.

Theory and hypothesis

As Toby E. Huff notes, pre-modern Chinese science developed precariously without solid scientific theory, while there was a lacking of consistent systemic treatment in comparison to contemporaneous European works such as the *Concordance and Discordant Canons* by Gratian of Bologna (fl. 12th century). This drawback to Chinese science was lamented even by the mathematician Yang Hui (1238–1298), who criticized earlier mathematicians such as Li Chunfeng (602–670) who were content with using methods without working out their theoretical origins or principle, stating:

The men of old changed the name of their methods from problem to problem, so that as no specific explanation was given, there is no way of telling their theoretical origin or basis.

Despite this, Chinese thinkers of the Middle Ages proposed some hypotheses which are in accordance with modern principles of science. Yang Hui provided theoretical proof for the proposition that the complements of the parallelograms which are about the diameter of any given parallelogram are equal to one another. Sun Sikong (1015–1076) proposed the idea that rainbows were the result of the contact between sunlight and moisture in the air, while Shen Kuo (1031–1095) expanded upon this with description of atmospheric refraction. Shen believed that rays of sunlight refracted before reaching the surface of the earth, hence the appearance of the observed sun from earth did not match its exact location. Coinciding with the astronomical work of his colleague Wei Pu, Shen and Wei realized that the old calculation technique for the mean sun was inaccurate compared to the apparent sun, since the latter was ahead of it in the accelerated phase of motion, and behind it in the retarded phase. Shen supported and expanded upon beliefs earlier proposed by Han dynasty (202 BCE–220 CE) scholars such as Jing Fang (78–37 BCE) and Zhang Heng (78–139 CE) that lunar eclipse occurs when the earth obstructs the sunlight traveling towards the moon, a solar eclipse is the moon's obstruction of sunlight reaching earth, the moon is spherical like a ball and not flat like a disc, and moonlight is merely sunlight reflected from the moon's surface. Shen also explained that the observance of a full moon occurred when the sun's light was slanting at a certain degree and that crescent phases of the moon proved that the moon was spherical, using a metaphor of observing different angles of a silver ball with white powder thrown onto one side. Although the Chinese accepted the idea of spherical-shaped heavenly bodies, the concept of a spherical earth (as opposed to a flat earth) was not accepted in Chinese thought until the works of Italian Jesuit Matteo Ricci (1552–1610) and Chinese astronomer Xu Guangqi (1562–1633) in the early 17th century.

Pharmacology

There were noted advances in traditional Chinese medicine during the Middle Ages. Emperor Gaozong (reigned 649–683) of the Tang dynasty (618–907) commissioned the scholarly compilation of a *materia medica* in 657 that documented 833 medicinal substances taken from stones, minerals, metals, plants, herbs, animals, vegetables, fruits, and cereal crops. In his *Bencao Tujing* ('Illustrated Pharmacopoeia'), the scholar-official Su Song (1020–1101) not only systematically categorized herbs and minerals according to their pharmaceutical uses, but he also took an interest in zoology. For example, Su made systematic descriptions of animal species and the environmental regions they could be found, such as the freshwater crab *Eriocher sinensis* found in the Huai River running through Anhui, in waterways near the capital city, as well as reservoirs and marshes of Hebei.

Muhammad ibn Zakariya al-Razi in 896, mentions the popular introduction of various Chinese herbs and aloes in Baghdad.

Horology and clockworks

Although the *Bencao Tujing* was an important pharmaceutical work of the age, Su Song is perhaps better known for his work in horology. His book *Xinyi Xiangfayao* (lit. 'Essentials of a New Method for Mechanizing the Rotation of an Armillary Sphere and a Celestial Globe') documented the intricate mechanics of his astronomical clock tower in Kaifeng. This included the use of an escapement mechanism and world's first known chain drive to power the rotating armillary sphere crowning the top as well as the 133 clock jack figurines positioned on a rotating wheel that sounded the hours by banging drums, clashing gongs, striking bells, and holding plaques with special announcements appearing from open-and-close shutter windows. While it had been Zhang Heng who applied the first motive power to the armillary sphere via hydraulics in 125 CE, it was Yi Xing (683–727) in 725 CE who first applied an escapement mechanism to a water-powered celestial globe and striking clock. The early Song Dynasty horologist Zhang Sixun (fl. late 10th century) employed liquid mercury in his astronomical clock because there were complaints that water would freeze too easily in the clepsydra tanks during winter.

Al-Jazari (1136–1206), a Muslim engineer and inventor of various clocks, including the Elephant clock, wrote: "[T]he elephant represents the Indian and African cultures, the two dragons represents Chinese culture, the phoenix represents Persian culture, the water work represents ancient Greek culture, and the turban represents Islamic culture".

Magnetism and metallurgy

Shen Kuo's written work of 1088 also contains the first written description of the magnetic needle compass, the first description in China of experiments with camera obscura, the invention of movable type printing by the artisan Bi Sheng (990–1051), a method of repeated forging of cast iron under a cold blast similar to the modern Bessemer process, and the mathematical basis for spherical trigonometry that would later be mastered by the astronomer and engineer Guo Shoujing (1231–1316). While using a sighting tube of improved width to correct the position of the pole star (which had shifted over the centuries), Shen discovered the concept of true north and magnetic declination towards the North Magnetic Pole, a concept which would aid navigators in the years to come.

In addition to the method similar to the Bessemer process mentioned above, there were other notable advancements in Chinese metallurgy during the Middle Ages. During the 11th century, the growth of the iron industry caused vast deforestation due to the use of charcoal in the smelting process. To remedy the problem of deforestation, the Song Chinese discovered how to produce coke from bituminous coal as a substitute for charcoal. Although hydraulic-powered bellows for heating the blast furnace had been written of since Du Shi's (d. 38) invention of the 1st century CE, the first known drawn and printed illustration of it in operation is found in a book written in 1313 by Wang Zhen (fl. 1290–1333).

Mathematics

Qin Jiushao (c. 1202–1261) was the first to introduce the zero symbol into Chinese mathematics. Before this innovation, blank spaces were used instead of zeros in the system of counting rods. Pascal's triangle was first illustrated in China by Yang Hui in his book *Xiangjie Jiuzhang Suanfa*, although it was described earlier around 1100 by Jia Xian. Although the *Introduction to Computational Studies* written by Zhu Shijie (fl. 13th century) in 1299 contained nothing new in Chinese algebra, it had a great impact on the development of Japanese mathematics.

Alchemy and Taoism

In their pursuit for an elixir of life and desire to create gold from various mixtures of materials, Taoists became heavily associated with alchemy. Joseph Needham labeled their pursuits as proto-scientific rather than merely pseudoscience. Fairbank and Goldman write that the futile experiments of Chinese alchemists did lead to the discovery of new metal alloys, porcelain types, and dyes. However, Nathan Sivin discounts such a close connection between Taoism and alchemy, which some sinologists have asserted, stating that alchemy was more prevalent in the secular sphere and practiced by laymen.

Experimentation with various materials and ingredients in China during the middle period led to the discovery of many ointments, creams, and other mixtures with practical uses. In a 9th-century Arab work *Kitāb al-Khawāss al Kabīr*, there are numerous products listed that were native to China, including waterproof and dust-repelling cream or varnish for clothes and weapons, a Chinese lacquer, varnish, or cream that protected leather items, a completely fire-proof cement for glass and porcelain, recipes for Chinese and Indian ink, a waterproof cream for the silk garments of underwater divers, and a cream specifically used for polishing mirrors.

Gunpowder warfare

The significant change that distinguished Medieval warfare to early Modern warfare was the use of gunpowder weaponry in battle. A 10th-century silken banner from Dunhuang portrays the first artistic depiction of a fire lance, a prototype of the gun. The *Wujing Zongyao* military manuscript of 1044 listed the first known written formulas for gunpowder, meant for light-weight bombs lobbed from catapults or thrown down from defenders behind city walls. By the 13th century, the iron-cased bomb shell, hand cannon, land mine, and rocket were developed. As evidenced by the *Huolongjing* of Jiao Yu and Liu Bowen, by the 14th century the Chinese had developed the heavy cannon, hollow and gunpowder-packed exploding cannonballs, the two-stage rocket with a booster rocket, the naval mine and wheellock mechanism to ignite trains of fuses.

Jesuit activity in China

The Jesuit China missions of the 16th and 17th centuries introduced Western science and astronomy, then undergoing its own revolution, to China. One modern historian writes that in late Ming courts, the Jesuits were "regarded as impressive especially for their knowledge of astronomy, calendar-making, mathematics, hydraulics, and geography." The Society of Jesus introduced, according to Thomas Woods, "a substantial body of scientific knowledge and a vast array of mental tools for understanding the physical universe, including the Euclidean geometry that made planetary motion comprehensible." Another expert quoted by Woods said the scientific revolution brought by the Jesuits coincided with a time when science was at a very low level in China:

[The Jesuits] made efforts to translate western mathematical and astronomical works into Chinese and aroused the interest of Chinese scholars in these sciences. They made very extensive astronomical observation and carried out the first modern cartographic work in China. They also learned to appreciate the scientific achievements of this ancient culture and made them known in Europe. Through their correspondence European scientists first learned about the Chinese science and culture.

Johann Adam Schall published Yuan Jing Shuo, Explanation of the Telescope, in 1626, in Latin and Chinese. Schall's book referred to the telescopic observations of Galileo.

Conversely, the Jesuits were very active in transmitting Chinese knowledge to Europe. Confucius's works were translated into European languages through the agency of Jesuit scholars stationed in China. Matteo Ricci started to report on the thoughts of Confucius, and Father Prospero Intorcetta published the life and works of Confucius into Latin in 1687. It is thought that such works had considerable importance on European thinkers of the period, particularly among the Deists and other philosophical groups of the Enlightenment who were interested by the integration of the system of morality of Confucius into Christianity.

The followers of the French physiocrat François Quesnay habitually referred to him as "the Confucius of Europe", and he personally identified himself with the Chinese sage. The doctrine and even the name of "Laissez-faire" may have been inspired by the Chinese concept of Wu wei. However, the economic insights of ancient Chinese political thought had otherwise little impact outside China in later centuries. Goethe, was known as "the Confucius of Weimar".

Scientific and technological stagnation

One question that has been the subject of debate among historians has been why China did not develop a scientific revolution and why Chinese technology fell behind that of Europe. Many hypotheses have been proposed ranging from the cultural to the political and economic. John K. Fairbank, for example, argued that the Chinese political system was hostile to scientific progress. As for Needham, he wrote that cultural factors prevented traditional Chinese achievements from developing into what could be called "science." It was the religious and philosophical framework of the Chinese intellectuals which made them unable to believe in the ideas of laws of nature:

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

Another prominent historian of science, Nathan Sivin, has argued that China indeed had a scientific revolution in the 17th century but it's just that we are still not able to really understand the scientific revolution that took place in China. Sivin suggests that we need to look at the scientific development in China on its own terms.

There are also questions about the philosophy behind traditional Chinese medicine, which, derived partly from Taoist philosophy, reflects the classical Chinese belief that individual human experiences express causative principles effective in the environment at all scales. Because its theory predates use of the scientific method, it has received various criticisms based on scientific thinking. Philosopher Robert Todd Carroll, a member of the Skeptics Society, deemed acupuncture a pseudoscience because it "confuse(s) metaphysical claims with empirical claims".

More recent historians have questioned political and cultural explanations and have put greater focus on economic causes. Mark Elvin's high level equilibrium trap is one well-known example of this line of thought. It argues that the Chinese population was large enough, workers cheap enough, and agrarian productivity high enough to not require mechanization: thousands of Chinese workers were perfectly able to quickly perform any needed task. Other events such as Haijin, the Opium Wars and the resulting hate of European influence prevented China from undergoing an Industrial Revolution; copying Europe's progress on a large scale would be impossible for a lengthy period of time. Political instability under Cixi rule (opposition and frequent oscillation between modernists and conservatives), the Republican wars (1911–1933), the Sino-Japanese War (1933–1945), the Communist/Nationalist War (1945–1949) as well as the later Cultural Revolution isolated China at the most critical times. Kenneth Pomeranz has made the argument that the substantial resources taken from the New World to Europe made the crucial difference between European and Chinese development.

In his book *Guns, Germs, and Steel*, Jared Diamond postulates that the lack of geographic barriers within much of China—essentially a wide plain with two large navigable rivers and a relatively smooth coastline—led to a single government without competition. At the whim of a ruler who disliked new inventions, technology could be stifled for half a century or more. In contrast, Europe's barriers of the Pyrenees, the Alps, and the various defensible peninsulas (Denmark, Scandinavia, Italy, Greece, etc.) and islands (Britain, Ireland, Sicily, etc.) led to smaller countries in constant competition with each other. If a ruler chose to ignore a scientific advancement (especially a military or economic one), his more-advanced neighbors would soon usurp his throne. This explanation, however, ignores the fact that China had been politically fragmented in the past, and was thus not inherently disposed to political unification.

The Republic of China (1912–49)

The Republic of China (1912–49) saw the introduction in earnest of modern science to China. Large numbers of Chinese students studied abroad in Japan and in Europe and the US. Many returned to help teach and to found numerous schools and universities. Among them were numerous outstanding figures, including Cai Yuanpei, Hu Shih, Weng Wenhao, Ding Wenjiang, Fu Ssu-nien, and many others. As a result, there was a tremendous growth of modern science in China. As the Communist Party took over China's mainland in 1949, some of these Chinese scientists and institutions moved to Taiwan. The central science academy, Academia Sinica, also moved there.

People's Republic of China

After the establishment of the People's Republic in 1949, China reorganized its science establishment along Soviet lines.

Although the country regressed scientifically as a result of government policies which led to famine during the Great Leap Forward and political chaos during the Cultural Revolution, scientific research in nuclear weapons and satellite launching still gained great success. From 1975, science and technology was one of the Four Modernizations, and its high-speed development was declared essential to all national economic development by Deng Xiaoping. Other civilian technologies such as superconductivity and high-yield hybrid rice led to new developments due to the application of science to industry and foreign technology transfer.

As the People's Republic of China becomes better connected to the global economy, the government has placed more emphasis on science and technology. This has led to increases in funding, improved scientific structure, and more money for research. These factors have led to advancements in agriculture, medicine, genetics, and global change. In 2003, the Chinese space program allowed China to become the third country to send humans into space, and ambition to put a man on mars by 2030. In the 2000s and 2010s, China became a top scientific and industrial power in more advanced fields such as super computing, artificial intelligence, bullet trains, aeronautics, nuclear physics researches and other fields.

In 2016, China became the country with the highest science output, as measured in publications. While the US had been the biggest producer of scientific studies until then, China published 426,000 studies in 2016 while the US published 409,000. However, the numbers are somewhat relative, as it also depends how authorship on international collaborations is counted (e.g. if one paper is counted per person or whether authorship is split among authors).

Chapter 31

History of Science in the Indian Subcontinent

The **history of science and technology in the Indian subcontinent** begins with prehistoric human activity in the Indus Valley Civilization to early states and empires. Following independence, science and technology in the Republic of India has included automobile engineering, information technology, communications as well as space, polar, and nuclear sciences.

Prehistory

By 5500 BCE a number of sites similar to Mehrgarh had appeared, forming the basis of later chalcolithic cultures. The inhabitants of these sites maintained trading relations with Near East and Central Asia.

Irrigation was developed in the Indus Valley Civilization by around 4500 BCE. The size and prosperity of the Indus civilization grew as a result of this innovation, which eventually led to more planned settlements making use of drainage and sewerage. Sophisticated irrigation and water storage systems were developed by the Indus Valley Civilization, including artificial reservoirs at Girnar dated to 3000 BCE, and an early canal irrigation system from c. 2600 BCE. Cotton was cultivated in the region by the 5th–4th millennia BCE. Sugarcane was originally from tropical South and Southeast Asia. Different species likely originated in different locations with *S. barberi* originating in India, and *S. edule* and *S. officinarum* coming from New Guinea.

The inhabitants of the Indus valley developed a system of standardization, using weights and measures, evident by the excavations made at the Indus valley sites. This technical standardization enabled gauging devices to be effectively used in angular measurement and measurement for construction. Calibration was also found in measuring devices along with multiple subdivisions in case of some devices. One of the earliest known docks is at Lothal (2400 BCE), located away from the main current to avoid deposition of silt. Modern oceanographers have observed that the Harappans must have possessed knowledge relating to tides in order to build such a dock on the ever-shifting course of the Sabarmati, as well as exemplary hydrography and maritime engineering.

Excavations at Balakot (c. 2500–1900 BCE), present day Pakistan, have yielded evidence of an early furnace. The furnace was most likely used for the manufacturing of ceramic objects. Ovens, dating back to the civilization's mature phase (c. 2500–1900 BCE), were also excavated at Balakot. The Kalibangan archeological site further yields evidence of potshaped hearths, which at one site have been found both on ground and underground. Kilns with fire and kiln chambers have also been found at the Kalibangan site.

Based on archaeological and textual evidence, Joseph E. Schwartzberg (2008)—a University of Minnesota professor emeritus of geography—traces the origins of Indian cartography to the Indus Valley Civilization (c. 2500–1900

BCE). The use of large scale constructional plans, cosmological drawings, and cartographic material was known in India with some regularity since the Vedic period (2nd – 1st millennium BCE). Climatic conditions were responsible for the destruction of most of the evidence, however, a number of excavated surveying instruments and measuring rods have yielded convincing evidence of early cartographic activity. Schwartzberg (2008)—on the subject of surviving maps—further holds that: 'Though not numerous, a number of map-like graffiti appear among the thousands of Stone Age Indian cave paintings; and at least one complex Mesolithic diagram is believed to be a representation of the cosmos.'

Archeological evidence of an animal-drawn plough dates back to 2500 BCE in the Indus Valley Civilization. The earliest available swords of copper discovered from the Harappan sites date back to 2300 BCE. Swords have been recovered in archaeological findings throughout the Ganges–Jamuna Doab region of India, consisting of bronze but more commonly copper.

Early kingdoms

The religious texts of the Vedic Period provide evidence for the use of large numbers. By the time of the last Veda, the

Yajurvedasaṃhitā (1200–900 BCE), numbers as high as were being included in the texts. For example, the *mantra* (sacrificial formula) at the end of the *annahoma* ("food-oblation rite") performed during the *aśvamedha* ("an allegory for a horse sacrifice"), and uttered just before-, during-, and just after sunrise, invokes powers of ten from a hundred to a trillion. The

Satapatha Brahmana (9th century BCE) contains rules for ritual geometric constructions that are similar to the Sulba Sutras.

Baudhayana (c. 8th century BCE) composed the *Baudhayana Sulba Sutra*, which contains examples of simple Pythagorean triples, such as: , , , , and as well as a statement of the Pythagorean theorem for the sides of a square: "The rope which is stretched across the diagonal of a square produces an area double the size of the original square." It also contains the general statement of the Pythagorean theorem (for the sides of a rectangle): "The rope stretched along the length of the diagonal of a rectangle makes an area which the vertical and horizontal sides make together." Baudhayana gives a formula for the square root of two. Mesopotamian influence at this stage is considered likely.

The earliest Indian astronomical text—named *Vedānga Jyotiṣa* and attributed to *Lagadha*—is considered one of the oldest astronomical texts, dating from 1400–1200 BCE (with the extant form possibly from 700–600 BCE), it details several astronomical attributes generally applied for timing social and religious events. It also details astronomical calculations, calendrical studies, and establishes rules for empirical observation. Since the *Vedānga Jyotiṣa* is a religious text, it has connections with Indian astrology and details several important aspects of the time and seasons, including lunar months, solar months, and their adjustment by a lunar leap month of *Adhikamāsa. Ritus* and *Yugas* are also described. Tripathi (2008) holds that "Twenty-seven constellations, eclipses, seven planets, and twelve signs of the zodiac were also known at that time."

The Egyptian *Papyrus of Kahun* (1900 BCE) and literature of the Vedic period in India offer early records of veterinary medicine. Kearns & Nash (2008) state that mention of leprosy is described in the medical treatise *Sushruta Samhita* (6th century BCE). The Sushruta Samhita an Ayurvedic text contains 184 chapters and description of 1120 illnesses, 700 medicinal plants, a detailed study on Anatomy, 64 preparations from mineral sources and 57 preparations based on animal sources. However, *The Oxford Illustrated Companion to Medicine* holds that the mention of leprosy, as well as ritualistic cures for it, were described in the Hindu religious book *Atharva-veda*, written in 1500–1200 BCE.

Cataract surgery was known to the physician Sushruta (6th century BCE). Traditional cataract surgery was performed with a special tool called the *Jabamukhi Salaka*, a curved needle used to loosen the lens and push the cataract out of the field of vision. The eye would later be soaked with warm butter and then bandaged. Though this method was successful, Susruta cautioned that it should only be used when necessary. The removal of cataract by surgery was also introduced into China from India.

During the 5th century BCE, the scholar Pāṇini had made several discoveries in the fields of phonetics, phonology, and morphology. Pāṇini's morphological analysis remained more advanced than any equivalent Western theory until the mid-20th century. Metal currency was minted in India before the 5th century BCE, with coinage (400 BCE–100 CE) being made of silver and copper, bearing animal and plant symbols on them.

Zinc mines of Zawar, near Udaipur, Rajasthan, were active during 400 BCE. Diverse specimens of swords have been discovered in Fatehgarh, where there are several varieties of hilt. These swords have been variously dated to periods between 1700–1400 BCE, but were probably used more extensively during the opening centuries of the 1st millennium BCE. Archaeological sites in such as Malhar, Dadupur, Raja Nala Ka Tila and Lahuradewa in present-day Uttar Pradesh show iron implements from the period between 1800 BCE and 1200 BCE. Early iron objects found in India can be dated to 1400 BCE by employing the method of radio carbon dating. Some scholars believe that by the early 13th century BCE iron smelting was practiced on a bigger scale in India, suggesting that the date of the technology's inception may be placed earlier. In Southern India (present day Mysore) iron appeared as early as 11th to 12th centuries BCE. These developments were too early for any significant close contact with the northwest of the country.

Middle Kingdoms (230 BCE – 1206 CE)

The *Arthashastra* of Kautilya mentions the construction of dams and bridges. The use of suspension bridges using plaited bamboo and iron chain was visible by about the 4th century. The *stupa*, the precursor of the pagoda and torii, was constructed by the 3rd century BCE. Rock-cut step wells in the region date from 200–400 CE. Subsequently, the construction of wells at Dhank (550–625 CE) and stepped ponds at Bhinmal (850–950 CE) took place.

During the 1st millennium BCE, the Vaisheshika school of atomism was founded. The most important proponent of this school was Kanada, an Indian philosopher who lived around 600 BCE. The school proposed that atoms are indivisible and eternal, can neither be created nor destroyed, and that each one possesses its own distinct *viśeṣa* (individuality). It was further elaborated on by the Buddhist school of atomism, of which the philosophers Dharmakirti and Dignāga in the 7th century CE were the most important proponents. They considered atoms to be point-sized, durationless, and made of energy.

By the beginning of the Common Era glass was being used for ornaments and casing in the region. Contact with the Greco-Roman world added newer techniques, and local artisans learnt methods of glass molding, decorating and coloring by the early centuries of the Common Era. The Satavahana period further reveals short cylinders of composite glass, including those displaying a lemon yellow matrix covered with green glass. Wootz originated in the region before the beginning of the common era. Wootz was exported and traded throughout Europe, China, the Arab world, and became particularly famous in the Middle East, where it became known as Damascus steel. Archaeological evidence suggests that manufacturing process for Wootz was also in existence in South India before the Christian era.

Evidence for using bow-instruments for carding comes from India (2nd century CE). The mining of diamonds and its early use as gemstones originated in India. Golconda served as an important early center for diamond mining and processing. Diamonds were then exported to other parts of the world. Early reference to diamonds comes from Sanskrit texts. The *Arthashastra* also mentions diamond trade in the region. The Iron pillar of Delhi was erected at the times of Chandragupta II Vikramaditya (375–413), which stood without rusting for around 2 millennium. The Rasaratna Samuccaya (800) explains the existence of two types of ores for zinc metal, one of which is ideal for metal extraction while the other is used for medicinal purpose.

The origins of the spinning wheel are unclear but India is one of the probable places of its origin. The device certainly reached Europe from India by the 14th century. The cotton gin was invented in India as a mechanical device known as *charkhi*, the "wooden-worm-worked roller". This mechanical device was, in some parts of the region, driven by water power. The Ajanta Caves yield evidence of a single roller cotton gin in use by the 5th century. This cotton gin was used until further innovations were made in form of foot powered gins. Chinese documents confirm at least two missions to India, initiated in 647, for obtaining technology for sugar-refining. Each mission returned with different results on refining sugar. Pingala (300–200 BCE) was a musical theorist who authored a Sanskrit treatise on prosody. There is evidence that in his work on the enumeration of syllabic combinations, Pingala stumbled upon both the Pascal triangle and Binomial coefficients, although he did not have knowledge of the Binomial theorem itself. A description of binary numbers is also found in the works of Pingala. The Indians also developed the use of the law of signs in multiplication. Negative numbers and the subtrahend had been used in East Asia since the 2nd century BCE, and Indian mathematicians were aware of negative numbers by the 7th century CE, and their role in mathematical problems of debt was understood. Although the Indians were not the first to use the subtrahend, they were the first to establish the "law of signs" with regards to the multiplication of positive and negative numbers, which did not appear in East Asian texts until 1299. Mostly consistent and correct rules for working with negative numbers were formulated, and the diffusion of these rules led the Arab intermediaries to pass it on to Europe.

A decimal number system using hieroglyphics dates back to 3000 BC in Egypt, and was later in use in ancient India. By the 9th century CE, the Hindu–Arabic numeral system was transmitted from the Middle East and to the rest of the world. The concept of 0 as a number, and not merely a symbol for separation is attributed to India. In India, practical calculations were carried out using zero, which was treated like any other number by the 9th century CE, even in case of division. Brahmagupta (598–668) was able to find (integral) solutions of Pell's equation. Conceptual design for a perpetual motion machine by Bhaskara II dates to 1150. He described a wheel that he claimed would run forever.

The trigonometric functions of sine and versine, from which it was trivial to derive the cosine, were used by the mathematician, Aryabhata, in the late 5th century. The calculus theorem now known as "Rolle's theorem" was stated by mathematician, Bhāskara II, in the 12th century.

Indigo was used as a dye in India, which was also a major center for its production and processing. The *Indigofera tinctoria* variety of Indigo was domesticated in India. Indigo, used as a dye, made its way to the Greeks and the Romans via various trade routes, and was valued as a luxury product. The cashmere wool fiber, also known as *pashm* or *pashmina*, was used in the handmade shawls of Kashmir. The woolen shawls from Kashmir region find written mention between 3rd century BCE and the 11th century CE. Crystallized sugar was discovered by the time of the Gupta dynasty, and the earliest reference to candied sugar comes from India. Jute was also cultivated in India. Muslin was named after the city where Europeans first encountered it, Mosul, in what is now Iraq, but the fabric actually originated from Dhaka in what is now Bangladesh. In the 9th century, an Arab merchant named Sulaiman makes note of the material's origin in Bengal (known as *Ruhml* in Arabic).

European scholar Francesco Lorenzo Pullè reproduced a number of Indian maps in his magnum opus *La Cartografia Antica dell India*. Out of these maps, two have been reproduced using a manuscript of *Lokaprakasa*, originally compiled by the polymath Ksemendra (Kashmir, 11th century CE), as a source. The other manuscript, used as a source by Francesco I, is titled *Samgraha'*.

Samarangana Sutradhara, a Sanskrit treatise by Bhoja (11th century), includes a chapter about the construction of mechanical contrivances (automata), including mechanical bees and birds, fountains shaped like humans and animals, and male and female dolls that refilled oil lamps, danced, played instruments, and re-enacted scenes from Hindu mythology.

Late Medieval and Early Modern periods (1206–1858 CE)

Madhava of Sangamagrama (c. 1340 – 1425) and his Kerala school of astronomy and mathematics developed and founded mathematical analysis. The infinite series for π was stated by him, and he made use of the series expansion of to obtain an infinite series expression, now known as the *Madhava-Gregory series*, for. Their rational approximation of the *error* for the finite sum of their series are of particular interest. They manipulated the error term to derive a faster converging series for. They used the improved series to derive a rational expression, for correct up to nine decimal places, *i.e.*(of 3.1415926535897...). The development of the series expansions for trigonometric functions (sine, cosine, and arc tangent) was carried out by mathematicians of the Kerala School in the 15th century CE. Their work, completed two centuries before the invention of calculus in Europe, provided what is now considered the first example of a power series (apart from geometric series).

Shēr Shāh of northern India issued silver currency bearing Islamic motifs, later imitated by the Mughal empire. The Chinese merchant Ma Huan (1413–51) noted that gold coins, known as *fanam*, were issued in Cochin and weighed a total of one *fen* and one *li* according to the Chinese standards. They were of fine quality and could be exchanged in China for 15 silver coins of four-*li* weight each.

In 1500, Nilakantha Somayaji of the Kerala school of astronomy and mathematics, in his Tantrasangraha, revised Aryabhata's elliptical model for the planets Mercury and Venus. His equation of the centre for these planets remained the most accurate until the time of Johannes Kepler in the 17th century.

The seamless celestial globe was invented in Kashmir by Ali Kashmiri ibn Luqman in 998 AH (1589–90 CE), and twenty other such globes were later produced in Lahore and Kashmir during the Mughal Empire. Before they were rediscovered in the 1980s, it was believed by modern metallurgists to be technically impossible to produce metal globes without any seams, even with modern technology. These Mughal metallurgists pioneered the method of lost-wax casting in order to produce these globes.

Gunpowder and gunpowder weapons were transmitted to India through the Mongol invasions of India. The Mongols were defeated by Alauddin Khalji of the Delhi Sultanate, and some of the Mongol soldiers remained in northern India after their conversion to Islam. It was written in the *Tarikh-i Firishta* (1606–1607) that the envoy of the Mongol ruler Hulagu Khan was presented with a pyrotechnics display upon his arrival in Delhi in 1258 CE. As a part of an embassy to India by Timurid leader Shah Rukh (1405–1447), 'Abd al-Razzaq mentioned naphtha-throwers mounted on elephants and a variety of pyrotechnics put on display. Firearms known as *top-o-tufak* also existed in the Vijayanagara Empire by as early as 1366 CE. From then on the employment of gunpowder warfare in the region was prevalent, with events such as the siege of Belgaum in 1473 CE by the Sultan Muhammad Shah Bahmani.

In *A History of Greek Fire and Gunpowder*, James Riddick Partington describes the gunpowder warfare of 16th and 17th century Mughal India, and writes that "Indian war rockets were formidable weapons before such rockets were used in Europe. They had bamboo rods, a rocket-body lashed to the rod, and iron points. They were directed at the target and fired by lighting the fuse, but the trajectory was rather erratic... The use of mines and counter-mines with explosive charges of gunpowder is mentioned for the times of Akbar and Jahāngir."

By the 16th century, Indians were manufacturing a diverse variety of firearms; large guns in particular, became visible in Tanjore, Dacca, Bijapur and Murshidabad. Guns made of bronze were recovered from Calicut (1504) and Diu (1533). Gujarāt supplied Europe saltpeter for use in gunpowder warfare during the 17th century. Bengal and Mālwa participated in saltpeter production. The Dutch, French, Portuguese, and English used Chhapra as a center of saltpeter refining.

The construction of water works and aspects of water technology in India is described in Arabic and Persian works. During medieval times, the diffusion of Indian and Persian irrigation technologies gave rise to an advanced irrigation system which bought about economic growth and also helped in the growth of material culture. The founder of the cashmere wool industry is traditionally held to be the 15th-century ruler of Kashmir, Zayn-ul-Abidin, who introduced weavers from Central Asia.

The scholar Sadiq Isfahani of Jaunpur compiled an atlas of the parts of the world which he held to be 'suitable for human life'.

The 32 sheet atlas—with maps oriented towards the south as was the case with Islamic works of the era—is part of a larger scholarly work compiled by Isfahani during 1647 CE. According to Joseph E. Schwartzberg (2008): 'The largest known Indian map, depicting the former Rajput capital at Amber in remarkable house-by-house detail, measures 661 × 645 cm. (260 × 254 in., or approximately 22 × 21 ft).'

Colonial era (1858–1947 CE)

Early volumes of the *Encyclopædia Britannica* described cartographic charts made by the seafaring Dravidian people. In *Encyclopædia Britannica (2008)*, Stephen Oliver Fought & John F. Guilmartin, Jr. describe the gunpowder technology in 18th-century Mysore:

Hyder Ali, prince of Mysore, developed war rockets with an important change: the use of metal cylinders to contain the combustion powder. Although the hammered soft iron he used was crude, the bursting strength of the container of black powder was much higher than the earlier paper construction. Thus a greater internal pressure was possible, with a resultant greater thrust of the propulsive jet. The rocket body was lashed with leather thongs to a long bamboo stick. Range was perhaps up to three-quarters of a mile (more than a kilometre). Although individually these rockets were not accurate, dispersion error became less important when large numbers were fired rapidly in mass attacks. They were particularly effective against cavalry and were hurled into the air, after lighting, or skimmed along the hard dry ground. Hyder Ali's son, Tippu Sultan, continued to develop and expand the use of rocket weapons, reportedly increasing the number of rocket troops from 1,200 to a corps of 5,000. In battles at Seringapatam in 1792 and 1799 these rockets were used with considerable effect against the British.

By the end of the 18th century the postal system in the region had reached high levels of efficiency. According to Thomas Broughton, the Maharaja of Jodhpur sent daily offerings of fresh flowers from his capital to Nathadvara (320 km) and they arrived in time for the first religious Darshan at sunrise. Later this system underwent modernization with the establishment of the British Raj. The Post Office Act XVII of 1837 enabled the Governor-General of India to convey messages by post within the territories of the East India Company. Mail was available to some officials without charge, which became a controversial privilege as the years passed. The Indian Post Office service was established on October 1, 1837. The British also constructed a vast railway network in the region for both strategic and commercial reasons.

The British education system, aimed at producing able civil and administrative services candidates, exposed a number of Indians to foreign institutions. Jagadis Chandra Bose (1858–1937), Prafulla Chandra Ray (1861–1944), Satyendra Nath Bose (1894–1974), Meghnad Saha (1893–1956), P. C. Mahalanobis (1893–1972), C. V. Raman (1888–1970), Subrahmanyan Chandrasekhar (1910–1995), Homi Bhabha (1909–1966), Srinivasa Ramanujan (1887–1920), Vikram Sarabhai (1919–1971), Har Gobind Khorana (1922–2011), Harish Chandra (1923–1983), and Abdus Salam (1926–1996) were among the notable scholars of this period.

Extensive interaction between colonial and native sciences was seen during most of the colonial era. Western science came to be associated with the requirements of nation building rather than being viewed entirely as a colonial entity, especially as it continued to fuel necessities from agriculture to commerce. Scientists from India also appeared throughout Europe. By the time of India's independence colonial science had assumed importance within the westernized intelligentsia and establishment.

French astronomer, Pierre Janssen observed the Solar eclipse of 18 August 1868 and discovered helium, from Guntur in Madras State, British India.

Chapter 32

History of Science in Korea

Like most other regions in the world, **science and technology in Korea** has experienced periods of intense growth as well as long periods of stagnation.

Prehistory

At the end of the Palaeolithic, people of the Korean Peninsula adopted microlithicstone tool technology, a highly efficient and useful way of making and maintaining a flexible prehistoric toolkit. The Palaeolithic also marks the beginning of a long period of plant and human interaction in which people undoubtedly adopted a number of wild plants for medicinal use.

Archaeological evidence from Gosan-ri in Jeju-do indicates that pottery was first made c. 8500-8000 BC. People depended on gathering, hunting, and fishing as the main source of food until the Middle Jeulmun Period (c. 3500 to 2000 BC) when small-scale cultivation of plants began.

The earliest known constellation patterns in Korea can be found on dolmens dating back to 3000 BC.

Farmers of the Mumun Period began to use multiple cropping systems of agriculture some time after 1500 BC. This advance in food production irrevocably altered the subsistence systems of the Mumun and hastened the beginnings of intensive agriculture in the Korean Peninsula. Korea and adjacent areas of East Asia seem to have been a part of the domestication region of soybean (*Glycine max*) between 1500 and 500 BC. Paddy-fieldagriculture, a system of wet-rice cultivation, was also introduced into the southern Korean Peninsula during this period.

Widespread archaeological evidence shows that after 850 BC the technology for heating homes changed. Before 850 BC pit-houses were heated using fire from various kinds of hearths that were dug into the floor of the pit-house. After 850 BC, hearths disappeared from the interior of pit-house architecture and was likely replaced with some kind of brazier-like technology in Hoseo, Honam, and western Yeongnam.

Bronze objects were exchanged into the Korean Peninsula from the outside before 900 BC. However, the moulds for bronze casting from Songguk-ri and an increased number of bronze artifacts indicates that people in the southern part of the peninsula engaged in bronze metallurgical production starting from c. 700 BC. Several hundred years later iron production was adopted, and Korean-made iron tools and weaponry became increasingly common after approximately 200 BC. Iron tools facilitated the spread of intensive agriculture into new areas of the Korean Peninsula.

Until recently, Koreans were thought to have invented under-floor heating, a system they call "ondol". It was first thought to have been invented by the people of the Northern Okjeo around 2,500 years ago. However, the recent discovery of a c. 3,000-year-old equivalent indoor heating system in Alaska has called current explanation into question. The absence of prehistoric and/or ancient ondol features in the area between the two archaeological sites makes it unlikely that the two systems might have come from the same source. However, there has also been hypothesis that whale-hunting people from the Korean peninsula have migrated to Alaska by sea during the time period, and this could explain the phenomenon.

Three Kingdoms Period

The production of hard-fired stoneware ceramics, in which clay is vitrified in kilns at >1000 °C, occurred first in the Korean Peninsula during the Three Kingdoms Period.

This period is notable for the establishment of industrial-scale production of pottery and roof tiles. This involved the adoption of Chinese dragon kiln or climbing kiln technology sometime between AD 100–300.

One of very few examples of science and technology during the Three Kingdoms of Korea that has survived until this day is the Cheomseongdae, which means "star gazing platform" and is one of the oldest observatories installed on Earth. It was built during Queen Seondeok's rule. The tower is built out of 366 pieces of cut granite which some claim represent the 366 days of the lunar year and has 12 base stones which supposedly represent the twelve months of the year. The design is said to be strongly influenced by Buddhism.

The nine-story wooden pagoda of Hwangnyongsa, which was commissioned by Queen Seondeok after the main temple was finished, is reputed to be the largest premodern Korean stupa ever built. It was reported to be 80 metres in height. Only its foundation stones remain today but they attest to the mammoth proportions of the original structure.

Goryeo Dynasty

During the Goryeo Dynastymetal movable type printing was invented by Choe Yun-ui in 1234. This invention made printing easier, more efficient and also increased literacy, which observed by Chinese visitors was seen to be so important where it was considered to be shameful to not be able to read. The Mongol Empire later adopted Korea's movable type printing and spread as far as Central Asia. There is conjecture as to whether or not Choe's invention had any influence on later printing inventions such as Gutenberg's Printing press. When the Mongolsinvaded Europe they inadvertently introduced different kinds of Asian technology.

During the late Goryeo Dynasty, Goryeo was at the cutting edge of shipboard artillery in world. In 1356 early experiments were carried out with gunpowder weapons that shot wood or metal projectiles. In 1373 experiments with incendiary arrows and "fire tubes" possibly an early form of the Hwacha were developed and placed on Korean warships. The policy of placing cannons and other gunpowder weapons continued well into the Joseon Dynasty and by 1410, over 160 Joseon warships had cannons on board. Choe Mu-seon, a medieval Korean inventor, military commander and scientist, introduced the widespread use of gunpowder to Korea for the first time and created various gunpowder-based weapons. The weapons were created because of Japanese pirates (Wokou) frequently raiding Korea's coastal regions. Choe obtained knowledge of gunpowder from a Chinese merchant named Lee Yuan despite the fact that it was against Mongol law. Lee was at first reluctant but eventually came around because he was impressed by Choe's patriotism and determination. Choe later impressed the Koryo court and King U which then built him a laboratory and a factory geared solely toward gunpowder. He invented the first Korean cannons and other weapons such as the Singijeon (Korean fire arrows) and later the Hwacha which were first built in 1377 and are widely considered to be the first true multiple rocket launchers. These weapons were a vast improvement over the previous rocket weapons with one of the key features was that it could fire up to 200 rockets at one time.

Joseon Dynasty

15th century

The Joseon Dynasty under the reign of Sejong the Great was Korea's greatest period of scientific advancement. In the first half of the 15th century, around 62 major accomplishments were made in various scientific fields. Of these, 29 came from Korea alone compared to 5 from China and 28 from the rest of the world.

Under Sejong's new policy Cheonmin (low-status) people such as Jang Yeong-sil were allowed to work for the government. At a young age, Jang displayed talent as an inventor and engineer, creating machines to facilitate agricultural work. These included supervising the building of aqueducts and canals. Jang eventually was allowed to live at the royal palace, where he led a group of scientists to work on advancing Korea's science.

Some of his inventions were an automated (self-striking) water clock (the Jagyeokru) which worked by activating motions of wooden figures to indicate time visually (invented in 1434 by Jang), a subsequent more complicated water-clock with additional astronomical devices, and an improved model of the previous metal movable printing type created in the Goryeo Dynasty. The new model was of even higher quality and was twice as fast. Other inventions were the sight glass, and the udometer.

The highpoint of Korean astronomy was during the Joseon period, where men such as Jang created devices such as celestial globes which indicated the positions of the sun, moon, and the stars. Later celestial globes (Gyupyo,) were attuned to the seasonal variations.

The apex of astronomical and calendarial advances under King Sejong was the Chiljeongsan, which compiled computations of the courses of the seven heavenly objects (five visible planets, the sun, and moon), developed in 1442. This work made it possible for scientists to calculate and accurately predict all the major heavenly phenomena, such as solar eclipses and other stellar movements. Honcheonsigye is an astronomical clock created by Song I-yeong in 1669. The clock has an armillary sphere with a diameter of 40 cm. The sphere is activated by a working clock mechanism, showing the position of celestial objects at any given time.

Kangnido, a Korean-made map of the world was created in 1402 by Kim Sa-hyeong, Yi Mu and Yi Hoe. The map was created in the second year of the reign of Taejong of Joseon. The map was made by combining Chinese, Korean and Japanese maps.

Hangul, the first and only featural alphabet in current use for a national language, was promulgated by Sejong in 1444.

16th-19th century

The scientific and technological advance in the late Joseon Dynasty was less progressed than the early Joseon period.

16th-century court physician, Heo Jun wrote a number of medical texts, his most significant achievement being Dongeui Bogam, which is often noted as the defining text of Traditional Korean medicine. The work spread to its East Asian neighbors, China and Japan, where it is still regarded as one of the classics of Oriental medicine today.

The first soft ballistic vest, Myunjebaegab, was invented in Joseon Korea in the 1860s shortly after the French campaign against Korea (1866). Heungseon Daewongun ordered development of bullet-proof armor because of increasing threats from Western armies. Kim Gi-du and Gang Yun found that cotton could protect against bullets if thick enough, and devised bullet-proof vests made of 30 layers of cotton. The vests were used in battle during the United States expedition to Korea (1871), when the US Navy attacked Ganghwa Island in 1871. The US Army captured one of the vests and took it to the US, where it was stored at the Smithsonian Museum until 2007. The vest has since been sent back to Korea and is currently on display to the public.

Modern period

North Korea

In late 1985 North Korea's first integrated circuit plant became operational. By the early 1990s, North Korea was producing about 20,000 computers a year, reportedly 60% were exported and the remainder were mostly for domestic military use. The development of a software industry started in the early 1990s. In general, software development is on a high level and it could become a major export item in the future, along with world-class voice recognition, automation and medical technology. North Korea has developed its own operating system, the *Red Star*, and has an intranet network named *Kwangmyong*, which contains censored content from the Internet. North Korean IT specialists demonstrate a high degree of technological literacy.

The National Aerospace Development Administration is the country's national space agency. As of 2010, two space launch facilities are operational - the Tonghae Satellite Launching Ground in North Hamgyong province, and the Tongch'ang-dong Space Launch Center in North Pyongan province. Kwangmyŏngsŏng-class satellites were launched from the former site by means of Paektusan and Unha rockets. So far, a total of three launch attempts were made, although none of them was successful.

North Korea is also researching and deploying various military technologies, such as GPS jammers, stealth paint, midget submarines and chemical, biological and nuclear weapons, anti-personnel lasers and ballistic missiles.

South Korea

Modern scientific and technological development in South Korea at first did not occur largely because of more pressing matters such as the division of Korea and the Korean War that occurred right after its independence. It wasn't until the 1960s under the dictatorship of Park Chung-hee where South Korea's economy rapidly grew from industrialisation and the Chaebol corporations such as Samsung and LG.

As of 2008 South Korea ranked 5th highest in terms of R&D. Park Kye-jung, CEO of Ace Electronics, won the Gold and Silver prizes for his invention of motor and motor-equipped gear at the 23rd Invention and New Product Exposition, he took the gold medal with his invention of a special device that converts vibrations from a running car into electric power. During the INPEX held in Pittsburgh, Pennsylvania sixteen Korean inventions received awards, including four gold prizes, three silvers, three bronzes and six special prizes. The Pittsburgh INPEX had inventors from 20 countries, contenders from Australia, Germany, the United States and 11 other countries submitted 160 items.

Seoul is ranked as the world's "leading digital city" and a "tech capital of the world". South Korea is also among the world's most technologically advanced and digitally connected countries; it has the third most broadband Internet users among the OECD countries and is a global leader in electronics, digital displays, semiconductor devices, and mobile phones.

The scientist Hwang Woo-suk, now officially disgraced, led a bio-engineering team that created three living clones of a dog that died in 2002.

Korea also exports radioactive isotope production equipment for medical and industrial use to countries such as Russia, Japan, Turkey and others.

Korea has a full-fledged space partnership with Russia and has launched the Arirang-1 and Arirang-2 satellites, both of which are equipped with surveillance cameras.

In robotics, KAIST competes with the Japanese company Honda with its humanoid robotHUBO. Honda's ASIMO and KAIST's HUBO lines are the two of very few humanoid robots that can walk. The first HUBO was developed within a span of 3 years and cost US$1 million.

In renewable energy, South Korean scientists at the Gwangju Institute of Science and Technology in cooperation with the University of California, Santa Barbara successfully developed an organic photovoltaic power cell with energy efficiency of 6.5 percent.

Results of a Statista study were released in August 2013 in regard to global smartphone penetration. After the United Arab Emirates (UAE), South Korea was the nation with the second-highest penetration level—73.0% of the population.

Following cyberattacks in the first half of 2013, in which government, news media, television station, and bank websites were compromised, the national government committed itself to training 5,000 new cybersecurity experts by 2017. The South

Korean government blamed its northern counterpart for these attacks, as well as for incidents that occurred in 2009, 2011, and 2012, but Pyongyang denies these accusations.

In late September 2013, a computer-security competition jointly sponsored by the defense ministry and the National Intelligence Service was announced. The winners will be announced on 29 September 2013 and will share a total prize pool of 80 million won (US$74,000).

Today, South Korea is known as a launchpad for developers into a mature mobile market with very few technology constraints. New types of media or apps using South Korea's 4G and 5G internet infrastructure are increasingly being developed. South Korea enjoys a convergence of a dense and prosperous population, excellent infrastructure, and a strong cultural identity.

Chapter 33

History of Botany

The **history of botany** examines the human effort to understand life on Earth by tracing the historical development of the discipline of botany—that part of natural science dealing with organisms traditionally treated as plants.

Rudimentary botanical science began with empirically-based plant lore passed from generation to generation in the oral traditions of paleolithic hunter-gatherers. The first written records of plants were made in the Neolithic Revolution about 10,000 years ago as writing was developed in the settled agricultural communities where plants and animals were first domesticated. The first writings that show human curiosity about plants themselves, rather than the uses that could be made of them, appear in ancient Greece and ancient India. In Ancient Greece, the teachings of Aristotle's student Theophrastus at the Lyceum in ancient Athens in about 350 BC are considered the starting point for Western botany. In ancient India, the Vŗkşăyurvĕda, attributed to Parăśara, is also considered one of the earliest texts to describe various branches of botany.

In Europe, botanical science was soon overshadowed by a medieval preoccupation with the medicinal properties of plants that lasted more than 1000 years. During this time, the medicinal works of classical antiquity were reproduced in manuscripts and books called herbals. In China and the Arab world, the Greco-Roman work on medicinal plants was preserved and extended.

In Europe the Renaissance of the 14th–17th centuries heralded a scientific revival during which botany gradually emerged from natural history as an independent science, distinct from medicine and agriculture. Herbals were replaced by floras: books that described the native plants of local regions. The invention of the microscope stimulated the study of plant anatomy, and the first carefully designed experiments in plant physiology were performed. With the expansion of trade and exploration beyond Europe, the many new plants being discovered were subjected to an increasingly rigorous process of naming, description, and classification.

Progressively more sophisticated scientific technology has aided the development of contemporary botanical offshoots in the plant sciences, ranging from the applied fields of economic botany (notably agriculture, horticulture and forestry), to the detailed examination of the structure and function of plants and their interaction with the environment over many scales from the large-scale global significance of vegetation and plant communities (biogeography and ecology) through to the small scale of subjects like cell theory, molecular biology and plant biochemistry.

Botany (Greek Βοτάνη - grass, fodder; Medieval Latin *botanicus* – herb, plant) and zoology are, historically, the core disciplines of biology whose history is closely associated with the natural sciences chemistry, physics and geology. A distinction can be made between botanical science in a pure sense, as the study of plants themselves, and botany as applied science, which studies the human use of plants. Early natural history divided pure botany into three main streams morphology-classification, anatomy and physiology – that is, external form, internal structure, and functional operation. The most obvious topics in applied botany are horticulture, forestry and agriculture although there are many others like weed science, plant pathology, floristry, pharmacognosy, economic botany and ethnobotany which lie outside modern courses in botany. Since the origin of botanical science there has been a progressive increase in the scope of the subject as technology has opened up new techniques and areas of study. Modern molecular systematics, for example, entails the principles and techniques of taxonomy, molecular biology, computer science and more.

Within botany there are a number of sub-disciplines that focus on particular plant groups, each with their own range of related studies (anatomy, morphology etc.). Included here are: phycology (algae), pteridology (ferns), bryology (mosses and liverworts) and palaeobotany (fossil plants) and their histories are treated elsewhere. To this list can be added mycology, the study of fungi, which were once treated as plants, but are now ranked as a unique kingdom.

Ancient knowledge

Nomadic hunter-gatherer societies passed on, by oral tradition, what they knew (their empirical observations) about the different kinds of plants that they used for food, shelter, poisons, medicines, for ceremonies and rituals etc. The uses of plants by these pre-literate societies influenced the way the plants were named and classified—their uses were embedded in folk-taxonomies, the way they were grouped according to use in everyday communication. The nomadic life-style was drastically changed when settled communities were established in about twelve centres around the world during the Neolithic Revolution which extended from about 10,000 to 2500 years ago depending on the region. With these communities came the development of the technology and skills needed for the domestication of plants and animals and the emergence of the written word provided evidence for the passing of systematic knowledge and culture from one generation to the next.

Plant lore and plant selection

During the Neolithic Revolution plant knowledge increased most obviously through the use of plants for food and medicine. All of today's staple foods were domesticated in prehistoric times as a gradual process of selection of higher-yielding varieties took place, possibly unknowingly, over hundreds to thousands of years. Legumes were cultivated on all continents but cereals made up most of the regular diet: rice in East Asia, wheat and barley in the Middle east, and maize in Central and South America. By Greco-Roman times popular food plants of today, including grapes, apples, figs, and olives, were being listed as named varieties in early manuscripts. Botanical authority William Stearn has observed that "*cultivated plants are mankind's most vital and precious heritage from remote antiquity*".

It is also from the Neolithic, in about 3000 BC, that we glimpse the first known illustrations of plants and read descriptions of impressive gardens in Egypt. However protobotany, the first pre-scientific written record of plants, did not begin with food;

it was born out of the medicinal literature of Egypt, China, Mesopotamia and India. Botanical historian Alan Morton notes that agriculture was the occupation of the poor and uneducated, while medicine was the realm of socially influential shamans, priests, apothecaries, magicians and physicians, who were more likely to record their knowledge for posterity.

Early botany

- Ancient India

An early example of ancient Indian plant classification is found in the Rigveda, a collection of Vedic Sanskrit hymns from about 3700–3100 BP. Plants are divided into *vṛska* (trees), *osadhi* (herbs useful to humans) and *virudha* (creepers), with further subdivisions. The sacred Hindu text Atharvaveda divides plants into eight classes: *visakha* (spreading branches), *manjari* (leaves with long clusters), *sthambini* (bushy plants), *prastanavati* (which expands); *ekasṛnga* (those with monopodial growth), *pratanavati* (creeping plants), *amsumati* (with many stalks), and *kandini* (plants with knotty joints). The Taittiriya Samhita classifies the plant kingdom into *vṛksa*, *vana* and *druma* (trees), *visakha* (shrubs with spreading branches), *sasa* (herbs), *amsumali* (spreading plant), *vratati* (climber), *stambini* (bushy plant), *pratanavati* (creeper), and *alasala* (spreading on the ground). Other examples of early Indian taxonomy include Manusmriti, the Law book of Hindus, which classifies plants into eight major categories. Elaborate taxonomies also occur in the Charaka Samhitā, Sushruta Samhita and Vaisesika.

- Ancient China

In ancient China lists of different plants and herb concoctions for pharmaceutical purposes date back to at least the time of the Warring States (481 BC-221 BC). Many Chinese writers over the centuries contributed to the written knowledge of herbal pharmaceutics. The Han Dynasty (202 BC-220 AD) includes the notable work of the Huangdi Neijing and the famous pharmacologist Zhang Zhongjing. There were also the 11th century scientists and statesmen Su Song and Shen Kuo who compiled learned treatises on natural history, emphasising herbal medicine.

Theophrastus and the origin of botanical science

Ancient Athens, of the 6th century BC, was the busy trade centre at the confluence of Egyptian, Mesopotamian and Minoan cultures at the height of Greek colonisation of the Mediterranean. The philosophical thought of this period ranged freely through many subjects. Empedocles (490–430 BC) foreshadowed Darwinian evolutionary theory in a crude formulation of the mutability of species and natural selection. The physician Hippocrates (460–370 BC) avoided the prevailing superstition of his day and approached healing by close observation and the test of experience. At this time a genuine non-anthropocentric curiosity about plants emerged. The major works written about plants extended beyond the description of their medicinal uses to the topics of plant geography, morphology, physiology, nutrition, growth and reproduction.

Foremost among the scholars studying botany was Theophrastus of Eressus (Greek: Θεόφραστος; c. 371–287 BC) who has been frequently referred to as the "Father of Botany". He was a student and close friend of Aristotle (384–322 BC) and succeeded him as head of the Lyceum (an educational establishment like a modern university) in Athens with its tradition of peripatetic philosophy. Aristotle's special treatise on plants — θεωρίαπερὶφυτῶν — is now lost, although there are many botanical observations scattered throughout his other writings (these have been assembled by Christian Wimmer in *Phytologiae Aristotelicae Fragmenta*, 1836) but they give little insight into his botanical thinking. The Lyceum prided itself in a tradition of systematic observation of causal connections, critical experiment and rational theorizing. Theophrastus challenged the superstitious medicine employed by the physicians of his day, called rhizotomi, and also the control over medicine exerted by priestly authority and tradition. Together with Aristotle he had tutored Alexander the Great whose military conquests were carried out with all the scientific resources of the day, the Lyceum garden probably containing many botanical trophies collected during his campaigns as well as other explorations in distant lands. It was in this garden where he gained much of his plant knowledge.

Theophrastus's major botanical works were the *Enquiry into Plants* (*Historia Plantarum*) and *Causes of Plants* (*Causae Plantarum*) which were his lecture notes for the Lyceum. The opening sentence of the *Enquiry* reads like a botanical manifesto: "*We must consider the distinctive characters and the general nature of plants from the point of view of their morphology, their behaviour under external conditions, their* *mode of generation and the whole course of their life*". The *Enquiry* is 9 books of "applied" botany dealing with the forms and classification of plants and economic botany, examining the techniques of agriculture (relationship of crops to soil, climate, water and habitat) and horticulture. He described some 500 plants in detail, often including descriptions of habitat and geographic distribution, and he recognised some plant groups that can be recognised as modern-day plant families. Some names he used, like *Crataegus*, *Daucus* and *Asparagus* have persisted until today. His second book *Causes of Plants* covers plant growth and reproduction (akin to modern physiology). Like Aristotle he grouped plants into "trees", "undershrubs", "shrubs" and "herbs" but he also made several other important botanical distinctions and observations. He noted that plants could be annuals, perennials and biennials, they were also either monocotyledons or dicotyledons and he also noticed the difference between determinate and indeterminate growth and details of floral structure including the degree of fusion of the petals, position of the ovary and more. These lecture notes of Theophrastus comprise the first clear exposition of the rudiments of plant anatomy, physiology, morphology and ecology — presented in a way that would not be matched for another eighteen centuries.

Meanwhile, the study of medicinal plants was not being neglected and a full synthesis of ancient Greek pharmacology was compiled in *Materia Medica* c. 60 AD by Pedanius Dioscorides (c. 40-90 AD) who was a Greek physician with the Roman army. This work proved to be the definitive text on medicinal herbs, both oriental and occidental, for fifteen hundred years until the dawn of the European Renaissance being slavishly copied again and again throughout this period.

Though rich in medicinal information with descriptions of about 600 medicinal herbs, the botanical content of the work was extremely limited.

Ancient Rome

The Romans contributed little to the foundations of botanical science laid by the ancient Greeks, but made a sound contribution to our knowledge of applied botany as agriculture. In works titled *De Re Rustica* four Roman writers contributed to a compendium *Scriptores Rei Rusticae*, published from the Renaissance on, which set out the principles and practice of agriculture. These authors were Cato (234–149 BC), Varro (116–27 BC) and, in particular, Columella (4–70 AD) and Palladius (4th century AD). Roman encyclopaedist Pliny the Elder (23–79 AD) deals with plants in Books 12 to 26 of his 37-volume highly influential work *Naturalis Historia* in which he frequently quotes Theophrastus but with a lack of botanical insight although he does, nevertheless, draw a distinction between true botany on the one hand, and farming and medicine on the other. It is estimated that at the time of the Roman Empire between 1300 and 1400 plants had been recorded in the West.

Medieval knowledge

Medicinal plants of the early Middle Ages

In Western Europe, after Theophrastus, botany passed through a bleak period of 1800 years when little progress was made and, indeed, many of the early insights were lost. As Europe entered the Middle Ages (5th to 15th centuries), China, India and the Arab world enjoyed a golden age. Chinese philosophy had followed a similar path to that of the ancient Greeks. The Chinese dictionary-encyclopaedia Erh Ya probably dates from about 300 BC and describes about 334 plants classed as trees or shrubs, each with a common name and illustration. Between 100 and 1700 AD many new works on pharmaceutical botany were produced including encyclopaedic accounts and treatises compiled for the Chinese imperial court. These were free of superstition and myth with carefully researched descriptions and nomenclature; they included cultivation information and notes on economic and medicinal uses — and even elaborate monographs on ornamental plants. But there was no experimental method and no analysis of the plant sexual system, nutrition, or anatomy.

The 400-year period from the 9th to 13th centuries AD was the Islamic Renaissance, a time when Islamic culture and science thrived. Greco-Roman texts were preserved, copied and extended although new texts always emphasised the medicinal aspects of plants. Kurdish biologist Ābu ⍰anīfah Ā⍰mad ibn Dawūd Dīnawarī (828–896 AD) is known as the founder of Arabic botany; his *Kitâb al-nabât* ('Book of Plants') describes 637 species, discussing plant development from germination to senescence and including details of flowers and fruits. The Mutazilite philosopher and physician Ibn Sina (Avicenna) (c. 980–1037 AD) was another influential figure, his *The Canon of Medicine* being a landmark in the history of medicine treasured until the Enlightenment.

In India simple artificial plant classification systems of the Rigveda, Atharvaveda and Taittiriya Samhita became more botanical with the work of Parashara (c. 400 – c. 500 AD), the author of *Vṛksayurveda* (the science of life of trees). He made close observations of cells and leaves and divided plants into Dvimatrka (Dicotyledons) and Ekamatrka (Monocotyledons). The dicotyledons were further classified into groupings (ganas) akin to modern floral families: *Samiganiya* (Fabaceae), *Puplikagalniya* (Rutaceae), *Svastikaganiya* (Cruciferae), *Tripuspaganiya* (Cucurbitaceae), *Mallikaganiya* (Apocynaceae), and *Kurcapuspaganiya* (Asteraceae). Important medieval Indian works of plant physiology include the *Prthviniraparyam* of Udayana, *Nyayavindutika* of Dharmottara, *Saddarsana-samuccaya* of Gunaratna, and *Upaskara* of Sankaramisra.

The Silk Road

Following the fall of Constantinople (1453), the newly expanded Ottoman Empire welcomed European embassies in its capital, which in turn became the sources of plants from those regions to the east which traded with the empire. In the following century twenty times as many plants entered Europe along the Silk Road as had been transported in the previous two thousand years, mainly as bulbs. Others were acquired primarily for their alleged medicinal value. Initially Italy benefited from this new knowledge, especially Venice, which traded extensively with the East. From there these new plants rapidly spread to the rest of Western Europe. By the middle of the sixteenth century there was already a flourishing export trade of various bulbs from Turkey to Europe.

The Age of Herbals

In the European Middle Ages of the 15th and 16th centuries the lives of European citizens were based around agriculture but when printing arrived, with movable type and woodcut illustrations, it was not treatises on agriculture that were published, but lists of medicinal plants with descriptions of their properties or "virtues". These first plant books, known as herbals showed that botany was still a part of medicine, as it had been for most of ancient history. Authors of herbals were often curators of university gardens, and most herbals were derivative compilations of classic texts, especially *De Materia Medica*. However, the need for accurate and detailed plant descriptions meant that some herbals were more botanical than medicinal. German Otto Brunfels's (1464–1534) *Herbarum Vivae Icones* (1530) contained descriptions of about 47 species new to science combined with accurate illustrations. His fellow countryman Hieronymus Bock's (1498–1554) *Kreutterbuch* of 1539 described plants he found in nearby woods and fields and these were illustrated in the 1546 edition. However, it was Valerius Cordus (1515–1544) who pioneered the formal botanical description that detailed both flowers and fruits, some anatomy including the number of chambers in the ovary, and the type of ovule placentation. He also made observations on pollen and distinguished between inflorescence types. His five-volume *Historia Plantarum* was published about 18 years after his early death aged 29 in 1561–1563. In Holland Rembert Dodoens (1517–1585), in *Stirpium Historiae* (1583), included descriptions of many new species from the Netherlands in a scientific arrangement and in England William Turner (1515–1568) in his *Libellus De Re Herbaria*

Novus (1538) published names, descriptions and localities of many native British plants.

Herbals contributed to botany by setting in train the science of plant description, classification, and botanical illustration. Up to the 17th century botany and medicine were one and the same but those books emphasising medicinal aspects eventually omitted the plant lore to become modern pharmacopoeias; those that omitted the medicine became more botanical and evolved into the modern compilations of plant descriptions we call Floras. These were often backed by specimens deposited in a herbarium which was a collection of dried plants that verified the plant descriptions given in the Floras. The transition from herbal to Flora marked the final separation of botany from medicine.

The Renaissance and Age of Enlightenment (1550–1800)

The revival of learning during the European Renaissance renewed interest in plants. The church, feudal aristocracy and an increasingly influential merchant class that supported science and the arts, now jostled in a world of increasing trade. Sea voyages of exploration returned botanical treasures to the large public, private, and newly established botanic gardens, and introduced an eager population to novel crops, drugs and spices from Asia, the East Indies and the New World.

The number of scientific publications increased. In England, for example, scientific communication and causes were facilitated by learned societies like Royal Society (founded in 1660) and the Linnaean Society (founded in 1788): there was also the support and activities of botanical institutions like the Jardin du Roi in Paris, Chelsea Physic Garden, Royal Botanic Gardens Kew, and the Oxford and Cambridge Botanic Gardens, as well as the influence of renowned private gardens and wealthy entrepreneurial nurserymen. By the early 17th century the number of plants described in Europe had risen to about 6000. The 18th century Enlightenment values of reason and science coupled with new voyages to distant lands instigating another phase of encyclopaedic plant identification, nomenclature, description and illustration, "flower painting" possibly at its best in this period of history. Plant trophies from distant lands decorated the gardens of Europe's powerful and wealthy in a period of enthusiasm for natural history, especially botany (a preoccupation sometimes referred to as "botanophilia") that is never likely to recur. Often such exotic new plant imports (primarily from Turkey), when they first appeared in print in English, lacked common names in the language.

During the 18th century botany was one of the few sciences considered appropriate for genteel educated women. Around 1760, with the popularization of the Linnaean system, botany became much more widespread among educated women who painted plants, attended classes on plant classification, and collected herbarium specimens although emphasis was on the healing properties of plants rather than plant reproduction which had overtones of sexuality. Women began publishing on botanical topics and children's books on botany appeared by authors like Charlotte Turner Smith. Cultural authorities argued that education through botany created culturally and scientifically aware citizens, part of the thrust for 'improvement' that characterised the Enlightenment. However, in the early 19th century with the recognition of botany as an official science, women were again excluded from the discipline.

Botanical gardens and herbaria

Public and private gardens have always been strongly associated with the historical unfolding of botanical science. Early botanical gardens were physic gardens, repositories for the medicinal plants described in the herbals. As they were generally associated with universities or other academic institutions the plants were also used for study. The directors of these gardens were eminent physicians with an educational role as "scientific gardeners" and it was staff of these institutions that produced many of the published herbals.

The botanical gardens of the modern tradition were established in northern Italy, the first being at Pisa (1544), founded by Luca Ghini (1490–1556). Although part of a medical faculty, the first chair of *materia medica*, essentially a chair in botany, was established in Padua in 1533. Then in 1534, Ghini became Reader in *materia medica* at Bologna University, where Ulisse Aldrovandi established a similar garden in 1568 (see below). Collections of pressed and dried specimens were called a *hortus siccus*(garden of dry plants) and the first accumulation of plants in this way (including the use of a plant press) is attributed to Ghini. Buildings called herbaria housed these specimens mounted on card with descriptive labels. Stored in cupboards in systematic order they could be preserved in perpetuity and easily transferred or exchanged with other institutions, a taxonomic procedure that is still used today.

By the 18th century the physic gardens had been transformed into "order beds" that demonstrated the classification systems that were being devised by botanists of the day — but they also had to accommodate the influx of curious, beautiful and new plants pouring in from voyages of exploration that were associated with European colonial expansion.

From Herbal to Flora

Plant classification systems of the 17th and 18th centuries now related plants to one another and not to man, marking a return to the non-anthropocentric botanical science promoted by Theophrastus over 1500 years before. In England, various herbals in either Latin or English were mainly compilations and translations of continental European works, of limited relevance to the British Isles. This included the rather unreliable work of Gerard (1597). The first systematic attempt to collect information on British plants was that of Thomas Johnson (1629), who was later to issue his own revision of Gerard's work (1633–1636).

However Johnson was not the first apothecary or physician to organise botanical expeditions to systematise their local flora. In Italy Ulisse Aldrovandi (1522 – 1605) organised an expedition to the Sibylline mountains in Umbria in 1557, and compiled a local Flora. He then began to disseminate his findings amongst other European scholars, forming an early network of knowledge sharing "*molti amici in molti luoghi*" (many friends in many places), including Charles de l'Écluse (Clusius) (1526 – 1609) at Montpellier and Jean de Brancion at Malines. Between them they started developing Latin names for plants, in addition to their common names. The exchange of information and specimens between scholars was often associated with the founding of botanical gardens (above), and to this end Aldrovandi founded one of the earliest at his university in Bologna, the Orto Botanico di Bologna in 1568.

In France, Clusius journeyed throughout most of Western Europe, making discoveries in the vegetable kingdom along the way. He compiled Flora of Spain (1576), and Austria and Hungary (1583). He was the first to propose dividing plants into classes. Meanwhile, in Switzerland, from 1554, Conrad Gessner (1516 – 1565) made regular explorations of the Swiss Alps from his native Zurich and discovered many new plants. He proposed that there were groups or genera of plants. He said that each genus was composed of many species and that these were defined by similar flowers and fruits. This principle of organization laid the groundwork for future botanists. He wrote his important *Historia Plantarum* shortly before his death. At Malines, in Flanders he established and maintained the botanical gardens of Jean de Brancion from 1568 to 1573, and first encountered tulips.

This approach coupled with the new Linnaean system of binomial nomenclature resulted in plant encyclopaedias without medicinal information called *Floras* that meticulously described and illustrated the plants growing in particular regions. The 17th century also marked the beginning of experimental botany and application of a rigorous scientific method, while improvements in the microscope launched the new discipline of plant anatomy whose foundations, laid by the careful observations of Englishman Nehemiah Grew and Italian Marcello Malpighi, would last for 150 years.

Botanical exploration

More new lands were opening up to European colonial powers, the botanical riches being returned to European botanists for description. This was a romantic era of botanical explorers, intrepid plant hunters and gardener-botanists. Significant botanical collections came from: the West Indies (Hans Sloane (1660–1753)); China (James Cunningham); the spice islands of the East Indies (Moluccas, George Rumphius (1627–1702)); China and Mozambique (João de Loureiro (1717–1791)); West Africa (Michel Adanson (1727–1806)) who devised his own classification scheme and forwarded a crude theory of the mutability of species; Canada, Hebrides, Iceland, New Zealand by Captain James Cook's chief botanist Joseph Banks (1743–1820).

Classification and morphology

By the middle of the 18th century the botanical booty resulting from the era of exploration was accumulating in gardens and herbaria – and it needed to be systematically catalogued. This was the task of the taxonomists, the plant classifiers.

Plant classifications have changed over time from "artificial" systems based on general habit and form, to pre-evolutionary "natural" systems expressing similarity using one to many characters, leading to post-evolutionary "natural" systems that use characters to infer evolutionary relationships.

Italian physician Andrea Caesalpino (1519–1603) studied medicine and taught botany at the University of Pisa for about 40 years eventually becoming Director of the Botanic Garden of Pisa from 1554 to 1558. His sixteen-volume *De Plantis* (1583) described 1500 plants and his herbarium of 260 pages and 768 mounted specimens still remains. Caesalpino proposed classes based largely on the detailed structure of the flowers and fruit; he also applied the concept of the genus. He was the first to try and derive principles of natural classification reflecting the overall similarities between plants and he produced a classification scheme well in advance of its day. Gaspard Bauhin (1560–1624) produced two influential publications *Prodromus Theatrici Botanici* (1620) and *Pinax* (1623). These brought order to the 6000 species now described and in the latter he used binomials and synonyms that may well have influenced Linnaeus's thinking. He also insisted that taxonomy should be based on natural affinities.

To sharpen the precision of description and classification Joachim Jung (1587–1657) compiled a much-needed botanical terminology which has stood the test of time. English botanist John Ray (1623–1705) built on Jung's work to establish the most elaborate and insightful classification system of the day. His observations started with the local plants of Cambridge where he lived, with the *Catalogus Stirpium circa Cantabrigiam Nascentium* (1860) which later expanded to his *Synopsis Methodica Stirpium Britannicarum*, essentially the first British Flora. Although his *Historia Plantarum* (1682, 1688, 1704) provided a step towards a world Flora as he included more and more plants from his travels, first on the continent and then beyond. He extended Caesalpino's natural system with a more precise definition of the higher classification levels, deriving many modern families in the process, and asserted that all parts of plants were important in classification. He recognised that variation arises from both internal (genotypic) and external environmental (phenotypic) causes and that only the former was of taxonomic significance. He was also among the first experimental physiologists. The *Historia Plantarum* can be regarded as the first botanical synthesis and textbook for modern botany. According to botanical historian Alan Morton, Ray "influenced both the theory and the practice of botany more decisively than any other single person in the latter half of the seventeenth century". Ray's family system was later extended by Pierre Magnol (1638–1715) and Joseph de Tournefort (1656–1708), a student of Magnol, achieved notoriety for his botanical expeditions, his emphasis on floral characters in classification, and for reviving the idea of the genus as the basic unit of classification.

Above all it was Swedish Carl Linnaeus (1707–1778) who eased the task of plant cataloguing. He adopted a sexual system of classification using stamens and pistils as important characters. Among his most important publications were Systema Naturae (1735), Genera Plantarum (1737), and Philosophia Botanica (1751) but it was in his Species Plantarum (1753) that he gave every species a binomial thus setting the path for the future accepted method of designating the names of all organisms. Linnaean thought and books dominated the world of taxonomy for nearly a century. His sexual system was later elaborated by Bernard de Jussieu (1699–1777) whose nephew Antoine-Laurent de Jussieu (1748–

1836) extended it yet again to include about 100 orders (present-day families). Frenchman Michel Adanson (1727–1806) in his *Familles des Plantes* (1763, 1764), apart from extending the current system of family names, emphasized that a natural classification must be based on a consideration of all characters, even though these may later be given different emphasis according to their diagnostic value for the particular plant group. Adanson's method has, in essence, been followed to this day.

18th century plant taxonomy bequeathed to the 19th century a precise binomial nomenclature and botanical terminology, a system of classification based on natural affinities, and a clear idea of the ranks of family, genus and species — although the taxa to be placed within these ranks remains, as always, the subject of taxonomic research.

Anatomy

In the first half of the 18th century botany was beginning to move beyond descriptive science into experimental science. Although the microscope was invented in 1590 it was only in the late 17th century that lens grinding provided the resolution needed to make major discoveries. Antony van Leeuwenhoek is a notable example of an early lens grinder who achieved remarkable resolution with his single-lens microscopes. Important general biological observations were made by Robert Hooke (1635–1703) but the foundations of plant anatomy were laid by Italian Marcello Malpighi (1628–1694) of the University of Bologna in his *Anatome Plantarum* (1675) and Royal Society Englishman Nehemiah Grew (1628–1711) in his *The Anatomy of Plants Begun* (1671) and *Anatomy of Plants* (1682). These botanists explored what is now called developmental anatomy and morphology by carefully observing, describing and drawing the developmental transition from seed to mature plant, recording stem and wood formation. This work included the discovery and naming of parenchyma and stomata.

Physiology

In plant physiology research interest was focused on the movement of sap and the absorption of substances through the roots. Jan Helmont (1577–1644) by experimental observation and calculation, noted that the increase in weight of a growing plant cannot be derived purely from the soil, and concluded it must relate to water uptake. Englishman Stephen Hales (1677–1761) established by quantitative experiment that there is uptake of water by plants and a loss of water by transpiration and that this is influenced by environmental conditions: he distinguished "root pressure", "leaf suction" and "imbibition" and also noted that the major direction of sap flow in woody tissue is upward. His results were published in *Vegetable Staticks* (1727) He also noted that "air makes a very considerable part of the substance of vegetables". English chemist Joseph Priestley (1733–1804) is noted for his discovery of oxygen (as now called) and its production by plants. Later Jan Ingenhousz (1730–1799) observed that only in sunlight do the green parts of plants absorb air and release oxygen, this being more rapid in bright sunlight while, at night, the air (CO_2) is released from all parts. His results were published in *Experiments upon vegetables* (1779) and with this the foundations for 20th century studies of carbon fixation were laid. From his observations he sketched the cycle of carbon in nature even though the composition of carbon dioxide was yet to be resolved. Studies in plant nutrition had also progressed. In 1804 Nicolas-Théodore de Saussure's (1767–1845) *Recherches Chimiques sur la Végétation* was an exemplary study of scientific exactitude that demonstrated the similarity of respiration in both plants and animals, that the fixation of carbon dioxide includes water, and that just minute amounts of salts and nutrients (which he analyzed in chemical detail from plant ash) have a powerful influence on plant growth.

Plant sexuality

It was Rudolf Camerarius (1665–1721) who was the first to establish plant sexuality conclusively by experiment. He declared in a letter to a colleague dated 1694 and titled *De Sexu Plantarum Epistola* that "no ovules of plants could ever develop into seeds from the female style and ovary without first being prepared by the pollen from the stamens, the male sexual organs of the plant".

Much was learned about plant sexuality by unravelling the reproductive mechanisms of mosses, liverworts and algae. In his *Vergleichende Untersuchungen* of 1851 Wilhelm Hofmeister (1824–1877) starting with the ferns and bryophytes demonstrated that the process of sexual reproduction in plants entails an "alternation of generations" between sporophytes and gametophytes. This initiated the new field of comparative morphology which, largely through the combined work of William Farlow (1844–1919), Nathanael Pringsheim (1823–1894), Frederick Bower, Eduard Strasburger and others, established that an "alternation of generations" occurs throughout the plant kingdom.

Some time later the German academic and natural historian Joseph Kölreuter (1733–1806) extended this work by noting the function of nectar in attracting pollinators and the role of wind and insects in pollination. He also produced deliberate hybrids, observed the microscopic structure of pollen grains and how the transfer of matter from the pollen to the ovary inducing the formation of the embryo.

One hundred years after Camerarius, in 1793, Christian Sprengel (1750–1816) broadened the understanding of flowers by describing the role of nectar guides in pollination, the adaptive floral mechanisms used for pollination, and the prevalence of cross-pollination, even though male and female parts are usually together on the same flower.

Nineteenth-century foundations of modern botany

In about the mid-19th century scientific communication changed. Until this time ideas were largely exchanged by reading the works of authoritative individuals who dominated in their field: these were often wealthy and influential "gentlemen scientists". Now research was reported by the publication of "papers" that emanated from research "schools" that promoted the questioning of conventional wisdom. This process had started in the late 18th century when specialist journals began to appear. Even so, botany was greatly stimulated by the appearance of the first "modern" textbook, Matthias Schleiden's (1804–1881) *Grundzüge der Wissenschaftlichen Botanik*, published in English in 1849 as

Principles of Scientific Botany. By 1850 an invigorated organic chemistry had revealed the structure of many plant constituents. Although the great era of plant classification had now passed the work of description continued. Augustin de Candolle (1778–1841) succeeded Antoine-Laurent de Jussieu in managing the botanical project *Prodromus Systematis Naturalis Regni Vegetabilis* (1824–1841) which involved 35 authors: it contained all the dicotyledons known in his day, some 58000 species in 161 families, and he doubled the number of recognized plant families, the work being completed by his son Alphonse (1806–1893) in the years from 1841 to 1873.

Plant geography and ecology

The opening of the 19th century was marked by an increase in interest in the connection between climate and plant distribution. Carl Willdenow (1765–1812) examined the connection between seed dispersal and distribution, the nature of plant associations and the impact of geological history. He noticed the similarities between the floras of N America and N Asia, the Cape and Australia, and he explored the ideas of "centre of diversity" and "centre of origin". German Alexander von Humboldt (1769–1859) and Frenchman Aime Bonpland (1773–1858) published a massive and highly influential 30 volume work on their travels; Robert Brown (1773–1852) noted the similarities between the floras of S Africa, Australia and India, while Joakim Schouw (1789–1852) explored more deeply than anyone else the influence on plant distribution of temperature, soil factors, especially soil water, and light, work that was continued by Alphonse de Candolle (1806–1893). Joseph Hooker (1817–1911) pushed the boundaries of floristic studies with his work on Antarctica, India and the Middle East with special attention to endemism. August Grisebach (1814–1879) in *Die Vegetation der Erde* (1872) examined physiognomy in relation to climate and in America geographic studies were pioneered by Asa Gray (1810–1888).

Physiological plant geography, or ecology, emerged from floristic biogeography in the late 19th century as environmental influences on plants received greater recognition. Early work in this area was synthesised by Danish professor Eugenius Warming (1841–1924) in his book *Plantesamfund* (Ecology of Plants, generally taken to mark the beginning of modern ecology) including new ideas on plant communities, their adaptations and environmental influences. This was followed by another grand synthesis, the *Pflanzengeographie auf Physiologischer Grundlage* of Andreas Schimper (1856–1901) in 1898 (published in English in 1903 as Plant-geography upon a physiological basis translated by W. R. Fischer, Oxford: Clarendon press, 839 pp.)

Anatomy

During the 19th century German scientists led the way towards a unitary theory of the structure and life-cycle of plants. Following improvements in the microscope at the end of the 18th century, Charles Mirbel (1776–1854) in 1802 published his *Traité d'Anatomie et de Physiologie Végétale* and Johann Moldenhawer (1766–1827) published *Beyträge zur Anatomie der Pflanzen* (1812) in which he describes techniques for separating cells from the middle lamella. He identified vascular and parenchymatous tissues, described vascular bundles, observed the cells in the cambium, and interpreted tree rings.

He found that stomata were composed of pairs of cells, rather than a single cell with a hole.

Anatomical studies on the stele were consolidated by Carl Sanio (1832–1891) who described the secondary tissues and meristem including cambium and its action. Hugo von Mohl (1805–1872) summarized work in anatomy leading up to 1850 in *Die Vegetabilische Zelle* (1851) but this work was later eclipsed by the encyclopaedic comparative anatomy of Heinrich Anton de Bary in 1877. An overview of knowledge of the stele in root and stem was completed by Van Tieghem (1839–1914) and of the meristem by Karl Nägeli (1817–1891). Studies had also begun on the origins of the carpel and flower that continue to the present day.

Water relations

The riddle of water and nutrient transport through the plant remained. Physiologist Von Mohl explored solute transport and the theory of water uptake by the roots using the concepts of cohesion, transpirational pull, capillarity and root pressure. German dominance in the field of physiology was underlined by the publication of the definitive textbook on plant physiology synthesising the work of this period, Sach's *Vorlesungen über Pflanzenphysiologie* of 1882. There were, however, some advances elsewhere such as the early exploration of geotropism (the effect of gravity on growth) by Englishman Thomas Knight, and the discovery and naming of osmosis by Frenchman Henri Dutrochet (1776–1847).

Cytology

The cell nucleus was discovered by Robert Brown in 1831. Demonstration of the cellular composition of all organisms, with each cell possessing all the characteristics of life, is attributed to the combined efforts of botanist Matthias Schleiden and zoologist Theodor Schwann (1810–1882) in the early 19th century although Moldenhawer had already shown that plants were wholly cellular with each cell having its own wall and Julius von Sachs had shown the continuity protoplasm between cell walls.

From 1870 to 1880 it became clear that cell nuclei are never formed anew but always derived from the substance of another nucleus. In 1882 Flemming observed the longitudinal splitting of chromosomes in the dividing nucleus and concluded that each daughter nucleus received half of each of the chromosomes of the mother nucleus: then by the early 20th century it was found that the number of chromosomes in a given species is constant. With genetic continuity confirmed and the finding by Eduard Strasburger that the nuclei of reproductive cells (in pollen and embryo) have a reducing division (halving of chromosomes, now known as meiosis) the field of heredity was opened up. By 1926 Thomas Morgan was able to outline a theory of the gene and its structure and function. The form and function of plastids received similar attention, the association with starch being noted at an early date. With observation of the cellular structure of all organisms and the process of cell division and continuity of genetic material, the analysis of the structure of protoplasm and the cell wall as well as that of plastids and vacuoles –

what is now known as cytology, or cell theory became firmly established.

Later, the cytological basis of the gene-chromosome theory of heredity extended from about 1900–1944 and was initiated by the rediscovery of Gregor Mendel's (1822–1884) laws of plant heredity first published in 1866 in *Experiments on Plant Hybridization* and based on cultivated pea, *Pisum sativum*: this heralded the opening up of plant genetics. The cytological basis for gene-chromosome theory was explored through the role of polyploidy and hybridization in speciation and it was becoming better understood that interbreeding populations were the unit of adaptive change in biology.

Developmental morphology and evolution

Until the 1860s it was believed that species had remained unchanged through time: each biological form was the result of an independent act of creation and therefore absolutely distinct and immutable. But the hard reality of geological formations and strange fossils needed scientific explanation. Charles Darwin's *Origin of Species* (1859) replaced the assumption of constancy with the theory of descent with modification. Phylogeny became a new principle as "natural" classifications became classifications reflecting, not just similarities, but evolutionary relationships. Wilhelm Hofmeister established that there was a similar pattern of organization in all plants expressed through the alternation of generations and extensive homology of structures.

Polymath German intellect Johann Goethe (1749–1832) had interests and influence that extended into botany. In *Die*

Metamorphose der Pflanzen (1790) he provided a theory of plant morphology (he coined the word "morphology") and he included within his concept of "metamorphosis" modification during evolution, thus linking comparative morphology with phylogeny. Though the botanical basis of his work has been challenged there is no doubt that he prompted discussion and research on the origin and function of floral parts. His theory probably stimulated the opposing views of German botanists Alexander Braun (1805–1877) and Matthias Schleiden who applied the experimental method to the principles of growth and form that were later extended by Augustin de Candolle (1778–1841).

Carbon fixation (photosynthesis)

At the start of the 19th century the idea that plants could synthesize almost all their tissues from atmospheric gases had not yet emerged. The energy component of photosynthesis, the capture and storage of the Sun's radiant energy in carbon bonds (a process on which all life depends) was first elucidated in 1847 by Mayer, but the details of how this was done would take many more years. Chlorophyll was named in 1818 and its chemistry gradually determined, to be finally resolved in the early 20th century. The mechanism of photosynthesis remained a mystery until the mid-19th century when Sachs, in 1862, noted that starch was formed in green cells only in the presence of light and in 1882 he confirmed carbohydrates as the starting point for all other organic compounds in plants. The connection between the pigment chlorophyll and starch production was finally made in 1864 but tracing the precise biochemical pathway of starch formation did not begin until about 1915.

Nitrogen fixation

Significant discoveries relating to nitrogen assimilation and metabolism, including ammonification, nitrification and nitrogen fixation (the uptake of atmospheric nitrogen by symbiotic soil microorganisms) had to wait for advances in chemistry and bacteriology in the late 19th century and this was followed in the early 20th century by the elucidation of protein and amino-acid synthesis and their role in plant metabolism. With this knowledge it was then possible to outline the global nitrogen cycle.

Twentieth century

20th century science grew out of the solid foundations laid by the breadth of vision and detailed experimental observations of the 19th century. A vastly increased research force was now rapidly extending the horizons of botanical knowledge at all levels of plant organization from molecules to global plant ecology. There was now an awareness of the unity of biological structure and function at the cellular and biochemical levels of organisation. Botanical advance was closely associated with advances in physics and chemistry with the greatest advances in the 20th century mainly relating to the penetration of molecular organization. However, at the level of plant communities it would take until mid century to consolidate work on ecology and population genetics. By 1910 experiments using labelled isotopes were being used to elucidate plant biochemical pathways, to open the line of research leading to gene technology. On a more practical level research funding was now becoming available from agriculture and industry.

Molecules

In 1903 Chlorophylls a and b were separated by thin layer chromatography then, through the 1920s and 1930s, biochemists, notably Hans Krebs (1900–1981) and Carl (1896–1984) and Gerty Cori (1896–1957) began tracing out the central metabolic pathways of life. Between the 1930s and 1950s it was determined that ATP, located in mitochondria, was the source of cellular chemical energy and the constituent reactions of photosynthesis were progressively revealed. Then, in 1944 DNA was extracted for the first time. Along with these revelations there was the discovery of plant hormones or "growth substances", notably auxins, (1934) gibberellins (1934) and cytokinins (1964) and the effects of photoperiodism, the control of plant processes, especially flowering, by the relative lengths of day and night.

Following the establishment of Mendel's laws, the gene-chromosome theory of heredity was confirmed by the work of August Weismann who identified chromosomes as the hereditary material. Also, in observing the halving of the chromosome number in germ cells he anticipated work to follow on the details of meiosis, the complex process of redistribution of hereditary material that occurs in the germ cells. In the 1920s and 1930s population genetics combined the theory of evolution with Mendelian genetics to produce the modern synthesis. By the mid-1960s the molecular basis of metabolism and reproduction was firmly established through the new discipline of molecular biology. Genetic engineering, the insertion of genes into a host cell for cloning, began in the 1970s with the invention of recombinant DNA techniques and its commercial applications applied to agricultural crops followed in the 1990s. There was now the potential to identify organisms by molecular "fingerprinting" and to estimate the times in the past when critical evolutionary changes had occurred through the use of "molecular clocks".

Computers, electron microscopes and evolution

Increased experimental precision combined with vastly improved scientific instrumentation was opening up exciting new fields. In 1936 Alexander Oparin (1894–1980) demonstrated a possible mechanism for the synthesis of organic matter from inorganic molecules. In the 1960s it was determined that the Earth's earliest life-forms treated as plants, the cyanobacteria known as stromatolites, dated back some 3.5 billion years.

Mid-century transmission and scanning electron microscopy presented another level of resolution to the structure of matter, taking anatomy into the new world of "ultrastructure".

New and revised "phylogenetic" classification systems of the plant kingdom were produced by several botanists, including August Eichler. A massive 23 volume *Die natürlichen Pflanzenfamilien* was published by Adolf Engler & Karl Prantl over the period 1887 to 1915. Taxonomy based on gross morphology was now being supplemented by using characters revealed by pollen morphology, embryology, anatomy, cytology, serology, macromolecules and more. The introduction of computers facilitated the rapid analysis of large data sets used for numerical taxonomy (also called taximetrics or phenetics). The emphasis on truly natural phylogenies spawned the disciplines of cladistics and phylogenetic systematics. The grand taxonomic synthesis *An Integrated System of Classification of Flowering Plants* (1981) of American Arthur Cronquist (1919–1992) was superseded when, in 1998, the Angiosperm Phylogeny Group published a phylogeny of flowering plants based on the analysis of DNA sequences using the techniques of the new molecular systematics which was resolving questions concerning the earliest evolutionary branches of the angiosperms (flowering plants). The exact relationship of fungi to plants had for some time been uncertain. Several lines of evidence pointed to fungi being different from plants, animals and bacteria – indeed, more closely related to animals than plants. In the 1980s-90s molecular analysis revealed an evolutionary divergence of fungi from other organisms about 1 billion years ago – sufficient reason to erect a unique kingdom separate from plants.

Biogeography and ecology

The publication of Alfred Wegener's (1880–1930) theory of continental drift 1912 gave additional impetus to comparative physiology and the study of biogeography while ecology in the 1930s contributed the important ideas of plant community, succession, community change, and energy flows. From 1940 to 1950 ecology matured to become an independent discipline as Eugene Odum (1913–2002) formulated many of the concepts of ecosystem ecology, emphasising relationships between groups of organisms (especially material and energy relationships) as key factors in the field. Building on the extensive earlier work of Alphonse de Candolle, Nikolai Vavilov (1887–1943) from 1914 to 1940 produced accounts of the geography, centres of origin, and evolutionary history of economic plants.

Twenty-first century

In reviewing the sweep of botanical history it is evident that, through the power of the scientific method, most of the basic questions concerning the structure and function of plants have, in principle, been resolved. Now the distinction between pure and applied botany becomes blurred as our historically accumulated botanical wisdom at all levels of plant organisation is needed (but especially at the molecular and global levels) to improve human custodianship of planet earth. The most urgent unanswered botanical questions now relate to the role of plants as primary producers in the global cycling of life's basic ingredients: energy, carbon, hydrogen, oxygen, and nitrogen, and ways that our plant stewardship can help address the global environmental issues of resource management, conservation, human food security, biologically invasive organisms, carbon sequestration, climate change, and sustainability.

Chapter 34

History of Evolutionary Thought

Evolutionary thought, the recognition that species change over time and the perceived understanding of how such processes work, has roots in antiquity—in the ideas of the ancient Greeks, Romans, and Chinese as well as in medieval Islamic science. With the beginnings of modern biological taxonomy in the late 17th century, two opposed ideas influenced Western biological thinking: essentialism, the belief that every species has essential characteristics that are unalterable, a concept which had developed from medieval Aristotelian metaphysics, and that fit well with natural theology; and the development of the new anti-Aristotelian approach to modern science: as the Enlightenment progressed, evolutionary cosmology and the mechanical philosophy spread from the physical sciences to natural history. Naturalists began to focus on the variability of species; the emergence of paleontology with the concept of extinction further undermined static views of nature. In the early 19th century Jean-Baptiste Lamarck (1744–1829) proposed his theory of the transmutation of species, the first fully formed theory of evolution.

In 1858 Charles Darwin and Alfred Russel Wallace published a new evolutionary theory, explained in detail in Darwin's *On the Origin of Species* (1859). Unlike Lamarck, Darwin proposed common descent and a branching tree of life, meaning that two very different species could share a common ancestor. Darwin based his theory on the idea of natural selection: it synthesized a broad range of evidence from animal husbandry, biogeography, geology, morphology, and embryology. Debate over Darwin's work led to the rapid acceptance of the general concept of evolution, but the specific mechanism he proposed, natural selection, was not widely accepted until it was revived by developments in biology that occurred during the 1920s through the 1940s. Before that time most biologists regarded other factors as responsible for evolution. Alternatives to natural selection suggested during "the eclipse of Darwinism" (c. 1880 to 1920) included inheritance of acquired characteristics (neo-Lamarckism), an innate drive for change (orthogenesis), and sudden large mutations (saltationism). Mendelian genetics, a series of 19th-century experiments with pea plant variations rediscovered in 1900, was integrated with natural selection by Ronald Fisher, J. B. S. Haldane, and Sewall Wright during the 1910s to 1930s, and resulted in the founding of the new discipline of population genetics. During the 1930s and 1940s population genetics became integrated with other biological fields, resulting in a widely applicable theory of evolution that encompassed much of biology—the modern synthesis.

Following the establishment of evolutionary biology, studies of mutation and genetic diversity in natural populations, combined with biogeography and systematics, led to sophisticated mathematical and causal models of evolution. Paleontology and comparative anatomy allowed more detailed reconstructions of the evolutionary history of life. After the rise of molecular genetics in the 1950s, the field of molecular evolution developed, based on protein sequences and immunological tests, and later incorporating RNA and DNA studies. The gene-centered view of evolution rose to prominence in the 1960s, followed by the neutral theory of molecular evolution, sparking debates over adaptationism, the unit of selection, and the relative importance of genetic drift versus natural selection as causes of evolution. In the late 20th-century, DNA sequencing led to molecular phylogenetics and the reorganization of the tree of life into the three-domain system by Carl Woese. In addition, the newly recognized factors of symbiogenesis and horizontal gene transfer introduced yet more complexity into evolutionary theory. Discoveries in evolutionary biology have made a significant impact not just within the traditional branches of biology, but also in other academic disciplines (for example: anthropology and psychology) and on society at large.

Antiquity

Greeks

Proposals that one type of animal, even humans, could descend from other types of animals, are known to go back to the first pre-Socratic Greek philosophers. Anaximander of Miletus (c. 610—546 BC) proposed that the first animals lived in water, during a wet phase of the Earth's past, and that the first land-dwelling ancestors of mankind must have been born in water, and only spent part of their life on land. He also argued that the first human of the form known today must have been the child of a different type of animal (probably a fish), because man needs prolonged nursing to live. In the late nineteenth century, Anaximander was hailed as the "first Darwinist", but this characterization is no longer commonly agreed. Anaximander's hypothesis could be considered "evolution" in a sense, although not a Darwinian one.

Empedocles (c. 490—430 BC), argued that what we call birth and death in animals are just the mingling and separations of elements which cause the countless "tribes of mortal things." Specifically, the first animals and plants were like disjointed parts of the ones we see today, some of which survived by joining in different combinations, and then intermixing during the development of the embryo, and where "everything turned out as it would have if it were on purpose, there the creatures survived, being accidentally compounded in a suitable way." Other philosophers who became more influential at that time, including Plato (c. 428/427—348/347 BC), Aristotle (384—322 BC), and members of the Stoic school of philosophy, believed that the types of all things, not only living things, were fixed by divine design.

Plato was called by biologist Ernst Mayr "the great antihero of evolutionism," because he promoted belief in essentialism, which is also referred to as the theory of Forms. This theory holds that each natural type of object in the observed world is an imperfect manifestation of the ideal, form or "species" which defines that type. In his *Timaeus* for example, Plato has a character tell a story that the Demiurge created the cosmos and everything in it because, being good, and hence, "... free from jealousy, He desired that all things should be as like Himself as they could be." The creator created all conceivable forms of life, since "... without them the universe will be incomplete, for it will not contain every kind of animal which it ought to contain, if it is to be perfect." This "principle of plenitude"—the idea that all potential forms of life are essential to a perfect creation—greatly influenced Christian thought. However some historians of science have questioned how much influence Plato's essentialism had on natural philosophy by stating that many philosophers after Plato believed that species might be capable of transformation and that the idea that biologic species were fixed and possessed unchangeable essential characteristics did not become important until the beginning of biological taxonomy in the 17th and 18th centuries.

Aristotle, the most influential of the Greek philosophers in Europe, was a student of Plato and is also the earliest natural historian whose work has been preserved in any real detail. His writings on biology resulted from his research into natural history on and around the island of Lesbos, and have survived in the form of four books, usually known by their Latin names, *De anima* (*On the Soul*), *Historia animalium* (*History of Animals*), *De generatione animalium* (*Generation of Animals*), and *De partibus animalium* (*On the Parts of Animals*). Aristotle's works contain accurate observations, fitted into his own theories of the body's mechanisms. However, for Charles Singer, "Nothing is more remarkable than [Aristotle's] efforts to [exhibit] the relationships of living things as a *scala naturae*." This *scala naturae*, described in *Historia animalium*, classified organisms in relation to a hierarchical but static "Ladder of Life" or "great chain of being," placing them according to their complexity of structure and function, with organisms that showed greater vitality and ability to move described as "higher organisms." Aristotle believed that features of living organisms showed clearly that they had what he called a final cause, that is to say that their form suited their function. He explicitly rejected the view of Empedocles that living creatures might have originated by chance.

Other Greek philosophers, such as Zeno of Citium (334—262 BC) the founder of the Stoic school of philosophy, agreed with Aristotle and other earlier philosophers that nature showed clear evidence of being designed for a purpose; this view is known as teleology. The Roman Skeptic philosopher Cicero (106—43 BC) wrote that Zeno was known to have held the view, central to Stoic physics, that nature is primarily "directed and concentrated...to secure for the world...the structure best fitted for survival."

Chinese

Ancient Chinese thinkers such as Zhuang Zhou (c. 369—286 BC), a Taoist philosopher, expressed ideas on changing biological species. According to Joseph Needham, Taoism explicitly denies the fixity of biological species and Taoist philosophers speculated that species had developed differing attributes in response to differing environments. Taoism regards humans, nature and the heavens as existing in a state of "constant transformation" known as the *Tao*, in contrast with the more static view of nature typical of Western thought.

Roman Empire

Lucretius' poem *De rerum natura* provides the best surviving explanation of the ideas of the Greek Epicurean philosophers. It describes the development of the cosmos, the Earth, living things, and human society through purely naturalistic mechanisms, without any reference to supernatural involvement. *De rerum natura* would influence the cosmological and evolutionary speculations of philosophers and scientists during and after the Renaissance. This view was in strong contrast with the views of Roman philosophers of the Stoic school such as Seneca the Younger (c. 4 BC – AD 65), and Pliny the Elder (23—79 AD) who had a strongly teleological view of the natural world that influenced Christian theology. Cicero reports that the peripatetic and Stoic view of nature as an agency concerned most basically with producing life "best fitted for survival" was taken for granted among the Hellenistic elite.

Origen and Augustine

In line with earlier Greek thought, the third-century Christian philosopher and Church Father Origen of Alexandria argued that the creation story in the Book of Genesis should be interpreted as an allegory for the falling of human souls away from the glory of the divine, and not as a literal, historical account:

For who that has understanding will suppose that the first, and second, and third day, and the evening and the morning, existed without a sun, and moon, and stars? And that the first day was, as it were, also without a sky? And who is so foolish as to suppose that God, after the manner of a husbandman, planted a paradise in Eden, towards the east, and placed in it a tree of life, visible and palpable, so that one tasting of the fruit by the bodily teeth obtained life? And again, that one was a partaker of good and evil by masticating what was taken from the tree? And if God is said to walk in the paradise in the evening, and Adam to hide himself under a tree, I do not suppose that anyone doubts that these things figuratively indicate certain mysteries, the history having taken place in appearance, and not literally.

- *—Origen, On the First Principles IV.16*

In the fourth century AD, the bishop and theologian Augustine of Hippo followed Origen in arguing that the Genesis creation story should not be read too literally. In his book *De Genesi ad litteram* (*On the Literal Meaning of Genesis*), he stated that in some cases new creatures may have come about through the "decomposition" of earlier forms of life. For Augustine, "plant, fowl and animal life are not perfect ... but created in a state of potentiality," unlike what he considered the theologically perfect forms of angels, the firmament and the human soul. Augustine's idea 'that forms of life had been transformed "slowly over time"' prompted Father Giuseppe Tanzella-Nitti, Professor of Theology at the Pontifical Santa Croce University in Rome, to claim that Augustine had suggested a form of evolution.

Henry Fairfield Osborn wrote in *From the Greeks to Darwin* (1894):

"If the orthodoxy of Augustine had remained the teaching of the Church, the final establishment of Evolution would have come far earlier than it did, certainly during the eighteenth instead of the nineteenth century, and the bitter controversy over this truth of Nature would never have arisen. ...Plainly as the direct or instantaneous Creation of animals and plants appeared to be taught in Genesis, Augustine read this in the light of primary causation and the gradual development from the imperfect to the perfect of Aristotle. This most influential teacher thus handed down to his followers opinions which closely conform to the progressive views of those theologians of the present day who have accepted the Evolution theory."

In *A History of the Warfare of Science with Theology in Christendom* (1896), Andrew Dickson White wrote about Augustine's attempts to preserve the ancient evolutionary approach to the creation as follows:

"For ages a widely accepted doctrine had been that water, filth, and carrion had received power from the Creator to generate worms, insects, and a multitude of the smaller animals; and this doctrine had been especially welcomed by St. Augustine and many of the fathers, since it relieved the Almighty of making, Adam of naming, and Noah of living in the ark with these innumerable despised species."

In Augustine's *De Genesi contra Manichæos*, on Genesis he says: "To suppose that God formed man from the dust with bodily hands is very childish. ...God neither formed man with bodily hands nor did he breathe upon him with throat and lips." Augustine suggests in other work his theory of the later development of insects out of carrion, and the adoption of the old emanation or evolution theory, showing that "certain very small animals may not have been created on the fifth and sixth days, but may have originated later from putrefying matter." Concerning Augustine's *De Trinitate* (*On the Trinity*), White wrote that Augustine "...develops at length the view that in the creation of living beings there was something like a growth—that God is the ultimate author, but works through secondary causes; and finally argues that certain substances are endowed by God with the power of producing certain classes of plants and animals."

Middle Ages

Islamic philosophy and the struggle for existence

Although Greek and Roman evolutionary ideas died out in Europe after the fall of the Roman Empire, they were not lost to Islamic philosophers and scientists. In the Islamic Golden Age of the 8th to the 13th centuries, philosophers explored ideas about natural history. These ideas included transmutation from non-living to living: "from mineral to plant, from plant to animal, and from animal to man."

In the medieval Islamic world, the scholar al-Jāḥiẓ (776 – c. 868) wrote his *Book of Animals* in the 9th century. Conway Zirkle, writing about the history of natural selection in 1941, said that an excerpt from this work was the only relevant passage he had found from an Arabian scholar. He provided a quotation describing the struggle for existence, citing a Spanish translation of this work: "Every weak animal devours those weaker than itself. Strong animals cannot escape being devoured by other animals stronger than they. And in this respect, men do not differ from animals, some with respect to others, although they do not arrive at the same extremes. In short, God has disposed some human beings as a cause of life for others, and likewise, he has disposed the latter as a cause of the death of the former." Al-Jāḥiẓ also wrote descriptions of food chains.

Some of Ibn Khaldūn's thoughts, according to some commentators, anticipate the biological theory of evolution. In 1377, Ibn Khaldūn wrote the *Muqaddimah* in which he asserted that humans developed from "the world of the monkeys," in a process by which "species become more numerous". In chapter 1 he writes: "This world with all the created things in it has a certain order and solid construction. It shows nexuses between causes and things caused, combinations of some parts of creation with others, and transformations of some existent things into others, in a pattern that is both remarkable and endless."

The *Muqaddimah* also states in chapter:

"We explained there that the whole of existence in (all) its simple and composite worlds is arranged in a natural order of ascent and descent, so that everything constitutes an uninterrupted continuum. The essences at the end of each particular stage of the worlds are by nature prepared to be transformed into the essence adjacent to them, either above or below them. This is the case with the simple material elements; it is the case with palms and vines, (which constitute) the last stage of plants, in their relation to snails and shellfish, (which constitute) the (lowest) stage of animals. It is also the case with monkeys, creatures combining in themselves cleverness and perception, in their relation to man, the being who has the ability to think and to reflect. The preparedness (for transformation) that exists on either side, at each stage of the worlds, is meant when (we speak about) their connection."

Christian philosophy

During the Early Middle Ages, Greek classical learning was all but lost to the West. However, contact with the Islamic world, where Greek manuscripts were preserved and expanded, soon led to a massive spate of Latin translations in the 12th century. Europeans were re-introduced to the works of Plato and Aristotle, as well as to Islamic thought. Christian thinkers of the scholastic school, in particular Peter Abelard (1079–1142) and Thomas Aquinas (1225–1274), combined Aristotelian classification with Plato's ideas of the goodness of God, and of all potential life forms being present in a perfect creation, to organize all inanimate, animate, and spiritual beings into a huge interconnected system: the *scala naturae*, or great chain of being.

Within this system, everything that existed could be placed in order, from "lowest" to "highest," with Hell at the bottom and God at the top—below God, an angelic hierarchy marked by the orbits of the planets, mankind in an intermediate position, and worms the lowest of the animals. As the universe was ultimately perfect, the great chain of being was also perfect. There were no empty links in the chain, and no link was represented by more than one species. Therefore, no species could ever move from one position to another. Thus, in this Christianized version of Plato's perfect universe, species could never change, but remained forever fixed, in accordance with the text of the Book of Genesis. For humans to forget their position was seen as sinful, whether they behaved like lower animals or aspired to a higher station than was given them by their Creator.

Creatures on adjacent steps were expected to closely resemble each other, an idea expressed in the saying: *natura non facit saltum* ("nature does not make leaps"). This basic concept of the great chain of being greatly influenced the thinking of Western civilization for centuries (and still has an influence today). It formed a part of the argument from design presented by natural theology. As a classification system, it became the major organizing principle and foundation of the emerging science of biology in the 17th and 18th centuries.

Thomas Aquinas on creation and natural processes

While Christian theologians held that the natural world was part of an unchanging designed hierarchy, some theologians speculated that the world might have developed through natural processes. Thomas Aquinas went even farther than Augustine of Hippo in arguing that scriptural texts like Genesis should not be interpreted in a literal way that conflicted with or constrained what natural philosophers learned about the workings of the natural world. He saw that the autonomy of nature was a sign of God's goodness, and detected no conflict between a divinely created universe and the idea that the universe had developed over time through natural mechanisms. However, Aquinas disputed the views of those (like the ancient Greek philosopher Empedocles) who held that such natural processes showed that the universe could have developed without an underlying purpose. Aquinas rather held that: "Hence, it is clear that nature is nothing but a certain kind of art, i.e., the divine art, impressed upon things, by which these things are moved to a determinate end.

It is as if the shipbuilder were able to give to timbers that by which they would move themselves to take the form of a ship."

Renaissance and Enlightenment

In the first half of the 17th century, René Descartes' mechanical philosophy encouraged the use of the metaphor of the universe as a machine, a concept that would come to characterise the scientific revolution. Between 1650 and 1800, some naturalists, such as Benoît de Maillet, produced theories that maintained that the universe, the Earth, and life, had developed mechanically, without divine guidance. In contrast, most contemporary theories of evolution, such of those of Gottfried Leibniz and Johann Gottfried Herder, regarded evolution as a fundamentally *spiritual* process. In 1751, Pierre Louis Maupertuis veered toward more materialist ground. He wrote of natural modifications occurring during reproduction and accumulating over the course of many generations, producing races and even new species, a description that anticipated in general terms the concept of natural selection.

Maupertuis' ideas were in opposition to the influence of early taxonomists like John Ray. In the late 17th century, Ray had given the first formal definition of a biological species, which he described as being characterized by essential unchanging features, and stated the seed of one species could never give rise to another. The ideas of Ray and other 17th-century taxonomists were influenced by natural theology and the argument from design.

The word *evolution* (from the Latin *evolutio*, meaning "to unroll like a scroll") was initially used to refer to embryological development; its first use in relation to development of species came in 1762, when Charles Bonnet used it for his concept of "pre-formation," in which females carried a miniature form of all future generations. The term gradually gained a more general meaning of growth or progressive development.

Later in the 18th century, the French philosopher Georges-Louis Leclerc, Comte de Buffon, one of the leading naturalists of the time, suggested that what most people referred to as species were really just well-marked varieties, modified from an original form by environmental factors. For example, he believed that lions, tigers, leopards, and house cats might all have a common ancestor. He further speculated that the 200 or so species of mammals then known might have descended from as few as 38 original animal forms. Buffon's evolutionary ideas were limited; he believed each of the original forms had arisen through spontaneous generation and that each was shaped by "internal moulds" that limited the amount of change. Buffon's works, *Histoire naturelle* (1749–1789) and *Époques de la nature* (1778), containing well-developed theories about a completely materialistic origin for the Earth and his ideas questioning the fixity of species, were extremely influential. Another French philosopher, Denis Diderot, also wrote that living things might have first arisen through spontaneous generation, and that species were always changing through a constant process of experiment where new forms arose and survived or not based on trial and error; an idea that can be considered a partial anticipation of natural selection. Between 1767 and 1792, James Burnett, Lord Monboddo, included in his writings not only the concept that man had descended from primates, but also that, in response to the environment, creatures had found methods of transforming their characteristics over long time intervals. Charles Darwin's grandfather, Erasmus Darwin, published *Zoonomia* (1794–1796) which suggested that "all warm-blooded animals have arisen from one living filament." In his poem *Temple of Nature* (1803), he described the rise of life from minute organisms living in mud to all of its modern diversity.

Early 19th century

Paleontology and geology

In 1796, Georges Cuvier published his findings on the differences between living elephants and those found in the fossil record. His analysis identified mammoths and mastodons as distinct species, different from any living animal, and effectively ended a long-running debate over whether a species could become extinct. In 1788, James Hutton described gradual geological processes operating continuously over deep time. In the 1790s, William Smith began the process of ordering rock strata by examining fossils in the layers while he worked on his geologic map of England. Independently, in 1811, Cuvier and Alexandre Brongniart published an influential study of the geologic history of the region around Paris, based on the stratigraphic succession of rock layers. These works helped establish the antiquity of the Earth. Cuvier advocated catastrophism to explain the patterns of extinction and faunal succession revealed by the fossil record.

Knowledge of the fossil record continued to advance rapidly during the first few decades of the 19th century. By the 1840s, the outlines of the geologic timescale were becoming clear, and in 1841 John Phillips named three major eras, based on the predominant fauna of each: the Paleozoic, dominated by marine invertebrates and fish, the Mesozoic, the age of reptiles, and the current Cenozoic age of mammals. This progressive picture of the history of life was accepted even by conservative English geologists like Adam Sedgwick and William Buckland; however, like Cuvier, they attributed the progression to repeated catastrophic episodes of extinction followed by new episodes of creation. Unlike Cuvier, Buckland and some other advocates of natural theology among British geologists made efforts to explicitly link the last catastrophic episode proposed by Cuvier to the biblical flood.

From 1830 to 1833, geologist Charles Lyell published his multi-volume work *Principles of Geology*, which, building on Hutton's ideas, advocated a uniformitarian alternative to the catastrophic theory of geology. Lyell claimed that, rather than being the products of cataclysmic (and possibly supernatural) events, the geologic features of the Earth are better explained as the result of the same gradual geologic forces observable in the present day—but acting over immensely long periods of time. Although Lyell opposed evolutionary ideas (even questioning the consensus that the fossil record demonstrates a true progression), his concept that the Earth was shaped by forces working gradually over an extended period, and the immense age of the Earth assumed by his theories, would strongly influence future evolutionary thinkers such as Charles Darwin.

Transmutation of species

Jean-Baptiste Lamarck proposed, in his *Philosophie Zoologique* of 1809, a theory of the transmutation of species (*transformisme*). Lamarck did not believe that all living things shared a common ancestor but rather that simple forms of life were created continuously by spontaneous generation. He also believed that an innate life force drove species to become more complex over time, advancing up a linear ladder of complexity that was related to the great chain of being. Lamarck recognized that species adapted to their environment. He explained this by saying that the same innate force driving increasing complexity caused the organs of an animal (or a plant) to change based on the use or disuse of those organs, just as exercise affects muscles. He argued that these changes would be inherited by the next generation and produce slow adaptation to the environment. It was this secondary mechanism of adaptation through the inheritance of acquired characteristics that would become known as Lamarckism and would influence discussions of evolution into the 20th century.

A radical British school of comparative anatomy that included the anatomist Robert Edmond Grant was closely in touch with Lamarck's French school of *Transformationism*. One of the French scientists who influenced Grant was the anatomist Étienne Geoffroy Saint-Hilaire, whose ideas on the unity of various animal body plans and the homology of certain anatomical structures would be widely influential and lead to intense debate with his colleague Georges Cuvier. Grant became an authority on the anatomy and reproduction of marine invertebrates. He developed Lamarck's and Erasmus Darwin's ideas of transmutation and evolutionism, and investigated homology, even proposing that plants and animals had a common evolutionary starting point. As a young student, Charles Darwin joined Grant in investigations of the life cycle of marine animals. In 1826, an anonymous paper, probably written by Robert Jameson, praised Lamarck for explaining how higher animals had "evolved" from the simplest worms; this was the first use of the word "evolved" in a modern sense.

In 1844, the Scottish publisher Robert Chambers anonymously published an extremely controversial but widely read book entitled *Vestiges of the Natural History of Creation*. This book proposed an evolutionary scenario for the origins of the Solar System and of life on Earth. It claimed that the fossil record showed a progressive ascent of animals, with current animals branching off a main line that leads progressively to humanity. It implied that the transmutations lead to the unfolding of a preordained plan that had been woven into the laws that governed the universe. In this sense it was less completely materialistic than the ideas of radicals like Grant, but its implication that humans were only the last step in the ascent of animal life incensed many conservative thinkers. The high profile of the public debate over *Vestiges*, with its depiction of evolution as a progressive process, would greatly influence the perception of Darwin's theory a decade later.

Ideas about the transmutation of species were associated with the radical materialism of the Enlightenment and were attacked by more conservative thinkers. Cuvier attacked the ideas of Lamarck and Geoffroy, agreeing with Aristotle that species were immutable. Cuvier believed that the individual parts of an animal were too closely correlated with one another to allow for one part of the anatomy to change in isolation from the others, and argued that the fossil record showed patterns of catastrophic extinctions followed by repopulation, rather than gradual change over time. He also noted that drawings of animals and animal mummies from Egypt, which were thousands of years old, showed no signs of change when compared with modern animals. The strength of Cuvier's arguments and his scientific reputation helped keep transmutational ideas out of the mainstream for decades.

In Great Britain, the philosophy of natural theology remained influential. William Paley's 1802 book *Natural Theology* with its famous watchmaker analogy had been written at least in part as a response to the transmutational ideas of Erasmus Darwin. Geologists influenced by natural theology, such as Buckland and Sedgwick, made a regular practice of attacking the evolutionary ideas of Lamarck, Grant, and *Vestiges*. Although Charles Lyell opposed scriptural geology, he also believed in the immutability of species, and in his *Principles of Geology*, he criticized Lamarck's theories of development. Idealists such as Louis Agassiz and Richard Owen believed that each species was fixed and unchangeable because it represented an idea in the mind of the creator. They believed that relationships between species could be discerned from developmental patterns in embryology, as well as in the fossil record, but that these relationships represented an underlying pattern of divine thought, with progressive creation leading to increasing complexity and culminating in humanity. Owen developed the idea of "archetypes" in the Divine mind that would produce a sequence of species related by anatomical homologies, such as vertebrate limbs. Owen led a public campaign that successfully marginalized Grant in the scientific community. Darwin would make good use of the homologies analyzed by Owen in his own theory, but the harsh treatment of Grant, and the controversy surrounding *Vestiges*, showed him the need to ensure that his own ideas were scientifically sound.

Anticipations of natural selection

It is possible to look through the history of biology from the ancient Greeks onwards and discover anticipations of almost all of Charles Darwin's key ideas. As an example, Loren Eiseley has found isolated passages written by Buffon suggesting he was almost ready to piece together a theory of natural selection, but states that such anticipations should not be taken out of the full context of the writings or of cultural values of the time which made Darwinian ideas of evolution unthinkable.

When Darwin was developing his theory, he investigated selective breeding and was impressed by Sebright's observation that "A severe winter, or a scarcity of food, by destroying the weak and the unhealthy, has all the good effects of the most skilful selection" so that "the weak and the unhealthy do not live to propagate their infirmities." Darwin was influenced by Charles Lyell's ideas of environmental change causing ecological shifts, leading to what Augustin de Candolle had called a war between competing plant species, competition well described by the botanist William Herbert. Darwin was struck by Thomas Robert Malthus' phrase "struggle for existence" used of warring human tribes.

Several writers anticipated evolutionary aspects of Darwin's theory, and in the third edition of *On the Origin of Species* published in 1861 Darwin named those he knew about in an introductory appendix, *An Historical Sketch of the Recent Progress of Opinion on the Origin of Species*, which he expanded in later editions.

In 1813, William Charles Wells read before the Royal Society essays assuming that there had been evolution of humans, and recognising the principle of natural selection. Darwin and Alfred Russel Wallace were unaware of this work when they jointly published the theory in 1858, but Darwin later acknowledged that Wells had recognised the principle before them, writing that the paper "An Account of a White Female, part of whose Skin resembles that of a Negro" was published in 1818, and "he distinctly recognises the principle of natural selection, and this is the first recognition which has been indicated; but he applies it only to the races of man, and to certain characters alone."

Patrick Matthew wrote in his book *On Naval Timber and Arboriculture* (1831) of "continual balancing of life to circumstance. ... [The] progeny of the same parents, under great differences of circumstance, might, in several generations, even become distinct species, incapable of co-reproduction." Darwin implies that he discovered this work after the initial publication of the *Origin*. In the brief historical sketch that Darwin included in the 3rd edition he says "Unfortunately the view was given by Mr. Matthew very briefly in scattered passages in an Appendix to a work on a different subject ... He clearly saw, however, the full force of the principle of natural selection."

However, as historian of science Peter J. Bowler says, "Through a combination of bold theorizing and comprehensive evaluation, Darwin came up with a concept of evolution that was unique for the time." Bowler goes on to say that simple priority alone is not enough to secure a place in the history of science; someone has to develop an idea and convince others of its importance to have a real impact. Thomas Henry Huxley said in his essay on the reception of *On the Origin of Species*:

"The suggestion that new species may result from the selective action of external conditions upon the variations from their specific type which individuals present—and which we call "spontaneous," because we are ignorant of their causation—is as wholly unknown to the historian of scientific ideas as it was to biological specialists before 1858. But that suggestion is the central idea of the 'Origin of Species,' and contains the quintessence of Darwinism."

Natural selection

The biogeographical patterns Charles Darwin observed in places such as the Galápagos Islands during the second voyage of HMS *Beagle* caused him to doubt the fixity of species, and in 1837 Darwin started the first of a series of secret notebooks on transmutation. Darwin's observations led him to view transmutation as a process of divergence and branching, rather than the ladder-like progression envisioned by Jean-Baptiste Lamarck and others. In 1838 he read the new 6th edition of *An Essay on the Principle of Population*, written in the late 18th century by Thomas Robert Malthus. Malthus' idea of population growth leading to a struggle for survival combined with Darwin's knowledge on how breeders selected traits, led to the inception of Darwin's theory of natural selection. Darwin did not publish his ideas on evolution for 20 years. However, he did share them with certain other naturalists and friends, starting with Joseph Dalton Hooker, with whom he discussed his unpublished 1844 essay on natural selection. During this period he used the time he could spare from his other scientific work to slowly refine his ideas and, aware of the intense controversy around transmutation, amass evidence to support them. In September 1854 he began full-time work on writing his book on natural selection.

Unlike Darwin, Alfred Russel Wallace, influenced by the book *Vestiges of the Natural History of Creation*, already suspected that transmutation of species occurred when he began his career as a naturalist. By 1855, his biogeographical observations during his field work in South America and the Malay Archipelago made him confident enough in a branching pattern of evolution to publish a paper stating that every species originated in close proximity to an already existing closely allied species. Like Darwin, it was Wallace's consideration of how the ideas of Malthus might apply to animal populations that led him to conclusions very similar to those reached by Darwin about the role of natural selection. In February 1858, Wallace, unaware of Darwin's unpublished ideas, composed his thoughts into an essay and mailed them to Darwin, asking for his opinion. The result was the joint publication in July of an extract from Darwin's 1844 essay along with Wallace's letter. Darwin also began work on a short abstract summarising his theory, which he would publish in 1859 as *On the Origin of Species*.

1859–1930s: Darwin and his legacy

By the 1850s, whether or not species evolved was a subject of intense debate, with prominent scientists arguing both sides of the issue. The publication of Charles Darwin's *On the Origin of Species* fundamentally transformed the discussion over biological origins. Darwin argued that his branching version of evolution explained a wealth of facts in biogeography, anatomy, embryology, and other fields of biology. He also provided the first cogent mechanism by which evolutionary change could persist: his theory of natural selection.

One of the first and most important naturalists to be convinced by *Origin* of the reality of evolution was the British anatomist Thomas Henry Huxley. Huxley recognized that unlike the earlier transmutational ideas of Jean-Baptiste Lamarck and *Vestiges of the Natural History of Creation*, Darwin's theory provided a mechanism for evolution without supernatural involvement, even if Huxley himself was not completely convinced that natural selection was the key evolutionary mechanism. Huxley would make advocacy of evolution a cornerstone of the program of the X Club to reform and professionalise science by displacing natural theology with naturalism and to end the domination of British natural science by the clergy. By the early 1870s in English-speaking countries, thanks partly to these efforts, evolution had become the mainstream scientific explanation for the origin of species. In his campaign for public and scientific acceptance of Darwin's theory, Huxley made extensive use of new evidence for evolution from paleontology. This included evidence that birds had evolved from reptiles, including the discovery of *Archaeopteryx* in Europe, and a number of fossils of primitive birds with teeth found in North America. Another important line of evidence was the finding of fossils that helped trace the evolution of the horse from its small five-toed ancestors. However, acceptance of evolution among scientists in non-English speaking nations such as France, and the countries of southern Europe and Latin America was slower. An exception to this was Germany, where both August Weismann and Ernst Haeckel championed this idea: Haeckel used evolution to challenge the established tradition of metaphysical idealism in German biology, much as Huxley used it to challenge natural theology in Britain. Haeckel and other German scientists would take the lead in launching an ambitious programme to reconstruct the evolutionary history of life based on morphology and embryology.

Darwin's theory succeeded in profoundly altering scientific opinion regarding the development of life and in producing a small philosophical revolution. However, this theory could not explain several critical components of the evolutionary process. Specifically, Darwin was unable to explain the source of variation in traits within a species, and could not identify a mechanism that could pass traits faithfully from one generation to the next. Darwin's hypothesis of pangenesis, while relying in part on the inheritance of acquired characteristics, proved to be useful for statistical models of evolution that were developed by his cousin Francis Galton and the "biometric" school of evolutionary thought. However, this idea proved to be of little use to other biologists.

Application to humans

Charles Darwin was aware of the severe reaction in some parts of the scientific community against the suggestion made in *Vestiges of the Natural History of Creation* that humans had arisen from animals by a process of transmutation. Therefore, he almost completely ignored the topic of human evolution in *On the Origin of Species*. Despite this precaution, the issue featured prominently in the debate that followed the book's publication. For most of the first half of the 19th century, the scientific community believed that, although geology had shown that the Earth and life were very old, human beings had appeared suddenly just a few thousand years before the present. However, a series of archaeological discoveries in the 1840s and 1850s showed stone tools associated with the remains of extinct animals. By the early 1860s, as summarized in Charles Lyell's 1863 book *Geological Evidences of the Antiquity of Man*, it had become widely accepted that humans had existed during a prehistoric period—which stretched many thousands of years before the start of written history. This view of human history was more compatible with an evolutionary origin for humanity than was the older view. On the other hand, at that time there was no fossil evidence to demonstrate human evolution. The only human fossils found before the discovery of Java Man in the 1890s were either of anatomically modern humans or of Neanderthals that were too close, especially in the critical characteristic of cranial capacity, to modern humans for them to be convincing intermediates between humans and other primates.

Therefore, the debate that immediately followed the publication of *On the Origin of Species* centered on the similarities and differences between humans and modern apes. Carolus Linnaeus had been criticised in the 18th century for grouping humans and apes together as primates in his ground breaking classification system. Richard Owen vigorously defended the classification suggested by Georges Cuvier and Johann Friedrich Blumenbach that placed humans in a separate order from any of the other mammals, which by the early 19th century had become the orthodox view. On the other hand, Thomas Henry Huxley sought to demonstrate a close anatomical relationship between humans and apes. In one famous incident, which became known as the Great Hippocampus Question, Huxley showed that Owen was mistaken in claiming that the brains of gorillas lacked a structure present in human brains. Huxley summarized his argument in his highly influential 1863 book *Evidence as to Man's Place in Nature*. Another viewpoint was advocated by Lyell and Alfred Russel Wallace. They agreed that humans shared a common ancestor with apes, but questioned whether any purely materialistic mechanism could account for all the differences between humans and apes, especially some aspects of the human mind.

In 1871, Darwin published *The Descent of Man, and Selection in Relation to Sex*, which contained his views on human evolution. Darwin argued that the differences between the human mind and the minds of the higher animals were a matter of degree rather than of kind. For example, he viewed morality as a natural outgrowth of instincts that were beneficial to animals living in social groups. He argued that all the differences between humans and apes were explained by a combination of the selective pressures that came from our ancestors moving from the trees to the plains, and sexual selection. The debate over human origins, and over the degree of human uniqueness continued well into the 20th century.

Alternatives to natural selection

The concept of evolution was widely accepted in scientific circles within a few years of the publication of *Origin*, but the acceptance of natural selection as its driving mechanism was much less widespread. The four major alternatives to natural selection in the late 19th century were theistic evolution, neo-Lamarckism, orthogenesis, and saltationism. Alternatives supported by biologists at other times included structuralism, Georges Cuvier's teleological but non-evolutionary functionalism, and vitalism.

Theistic evolution was the idea that God intervened in the process of evolution, to guide it in such a way that the living world could still be considered to be designed. The term was promoted by Charles Darwin's greatest American advocate Asa Gray. However, this idea gradually fell out of favor among scientists, as they became more and more committed to the idea of methodological naturalism and came to believe that direct appeals to supernatural involvement were scientifically unproductive. By 1900, theistic evolution had largely disappeared from professional scientific discussions, although it retained a strong popular following.

In the late 19th century, the term neo-Lamarckism came to be associated with the position of naturalists who viewed the inheritance of acquired characteristics as the most important evolutionary mechanism. Advocates of this position included the British writer and Darwin critic Samuel Butler, the German biologist Ernst Haeckel, and the American paleontologist Edward Drinker Cope. They considered Lamarckism to be philosophically superior to Darwin's idea of selection acting on random variation. Cope looked for, and thought he found, patterns of linear progression in the fossil record. Inheritance of acquired characteristics was part of Haeckel's recapitulation theory of evolution, which held that the embryological development of an organism repeats its evolutionary history. Critics of neo-Lamarckism, such as the German biologist August Weismann and Alfred Russel Wallace, pointed out that no one had ever produced solid evidence for the inheritance of acquired characteristics. Despite these criticisms, neo-Lamarckism remained the most popular alternative to natural selection at the end of the 19th century, and would remain the position of some naturalists well into the 20th century.

Orthogenesis was the hypothesis that life has an innate tendency to change, in a unilinear fashion, towards ever-greater perfection. It had a significant following in the 19th century, and its proponents included the Russian biologist Leo S. Berg and the American paleontologist Henry Fairfield Osborn. Orthogenesis was popular among some paleontologists, who believed that the fossil record showed a gradual and constant unidirectional change.

Saltationism was the idea that new species arise as a result of large mutations. It was seen as a much faster alternative to the Darwinian concept of a gradual process of small random variations being acted on by natural selection, and was popular with early geneticists such as Hugo de Vries, William Bateson, and early in his career, Thomas Hunt Morgan. It became the basis of the mutation theory of evolution.

Mendelian genetics, biometrics, and mutation

The rediscovery of Gregor Mendel's laws of inheritance in 1900 ignited a fierce debate between two camps of biologists. In one camp were the Mendelians, who were focused on discrete variations and the laws of inheritance. They were led by William Bateson (who coined the word *genetics*) and Hugo de Vries (who coined the word *mutation*). Their opponents were the biometricians, who were interested in the continuous variation of characteristics within populations. Their leaders, Karl Pearson and Walter Frank Raphael Weldon, followed in the tradition of Francis Galton, who had focused on measurement and statistical analysis of variation within a population. The biometricians rejected Mendelian genetics on the basis that discrete units of heredity, such as genes, could not explain the continuous range of variation seen in real populations. Weldon's work with crabs and snails provided evidence that selection pressure from the environment could shift the range of variation in wild populations, but the Mendelians maintained that the variations measured by biometricians were too insignificant to account for the evolution of new species.

When Thomas Hunt Morgan began experimenting with breeding the fruit fly *Drosophila melanogaster*, he was a saltationist who hoped to demonstrate that a new species could be created in the lab by mutation alone. Instead, the work at his lab between 1910 and 1915 reconfirmed Mendelian genetics and provided solid experimental evidence linking it to chromosomal inheritance. His work also demonstrated that most mutations had relatively small effects, such as a change in eye color, and that rather than creating a new species in a single step, mutations served to increase variation within the existing population.

1920s–1940s

Population genetics

The Mendelian and biometrician models were eventually reconciled with the development of population genetics. A key step was the work of the British biologist and statistician Ronald Fisher. In a series of papers starting in 1918 and culminating in his 1930 book *The Genetical Theory of Natural Selection*, Fisher showed that the continuous variation measured by the biometricians could be produced by the combined action of many discrete genes, and that natural selection could change gene frequencies in a population, resulting in evolution. In a series of papers beginning in 1924, another British geneticist, J. B. S. Haldane, applied statistical analysis to real-world examples of natural selection, such as the evolution of industrial melanism in peppered moths, and showed that natural selection worked at an even faster rate than Fisher assumed.

The American biologist Sewall Wright, who had a background in animal breeding experiments, focused on combinations of interacting genes, and the effects of inbreeding on small, relatively isolated populations that exhibited genetic drift. In 1932, Wright introduced the concept of an adaptive landscape and argued that genetic drift and inbreeding could drive a small, isolated sub-population away from an adaptive peak, allowing natural selection to drive it towards different adaptive peaks. The work of Fisher, Haldane and Wright founded the discipline of population genetics. This integrated natural selection with Mendelian genetics, which was the critical first step in developing a unified theory of how evolution worked.

The modern synthesis

In the first few decades of the 20th century, most field naturalists continued to believe that alternative mechanisms of evolution such as Lamarckism and orthogenesis provided the best explanation for the complexity they observed in the living world. But as the field of genetics continued to develop, those views became less tenable. Theodosius Dobzhansky, a postdoctoral worker in Thomas Hunt Morgan's lab, had been influenced by the work on genetic diversity by Russian geneticists such as Sergei Chetverikov. He helped to bridge the divide between the foundations of microevolution developed by the population geneticists and the patterns of macroevolution observed by field biologists, with his 1937 book *Genetics and the Origin of Species*. Dobzhansky examined the genetic diversity of wild populations and showed that, contrary to the assumptions of the population geneticists, these populations had large amounts of genetic diversity, with marked differences between sub-populations. The book also took the highly mathematical work of the population geneticists and put it into a more accessible form. In Britain, E. B. Ford, the pioneer of ecological genetics, continued throughout the 1930s and 1940s to demonstrate the power of selection due to ecological factors including the ability to maintain genetic diversity through genetic polymorphisms such as human blood types. Ford's work would contribute to a shift in emphasis during the course of the modern synthesis towards natural selection over genetic drift.

The evolutionary biologist Ernst Mayr was influenced by the work of the German biologist Bernhard Rensch showing the influence of local environmental factors on the geographic distribution of sub-species and closely related species. Mayr followed up on Dobzhansky's work with the 1942 book *Systematics and the Origin of Species*, which emphasized the importance of allopatric speciation in the formation of new species. This form of speciation occurs when the geographical isolation of a sub-population is followed by the development of mechanisms for reproductive isolation. Mayr also formulated the biological species concept that defined a species as a group of interbreeding or potentially interbreeding populations that were reproductively isolated from all other populations.

In the 1944 book *Tempo and Mode in Evolution*, George Gaylord Simpson showed that the fossil record was consistent with the irregular non-directional pattern predicted by the developing evolutionary synthesis, and that the linear trends that earlier paleontologists had claimed supported orthogenesis and neo-Lamarckism did not hold up to closer examination. In 1950, G. Ledyard Stebbins published *Variation and Evolution in Plants*, which helped to integrate botany into the synthesis. The emerging cross-disciplinary consensus on the workings of evolution would be known as the modern synthesis. It received its name from the 1942 book *Evolution: The Modern Synthesis* by Julian Huxley.

The modern synthesis provided a conceptual core—in particular, natural selection and Mendelian population genetics—that tied together many, but not all, biological disciplines: developmental biology was one of the omissions. It helped establish the legitimacy of evolutionary biology, a primarily historical science, in a scientific climate that favored experimental methods over historical ones. The synthesis also resulted in a considerable narrowing of the range of mainstream evolutionary thought (what Stephen Jay Gould called the "hardening of the synthesis"): by the 1950s, natural selection acting on genetic variation was virtually the only acceptable mechanism of evolutionary change (panselectionism), and macroevolution was simply considered the result of extensive microevolution.

1940s–1960s: Molecular biology and evolution

The middle decades of the 20th century saw the rise of molecular biology, and with it an understanding of the chemical nature of genes as sequences of DNA and of their relationship—through the genetic code—to protein sequences. At the same time, increasingly powerful techniques for analyzing proteins, such as protein electrophoresis and sequencing, brought biochemical phenomena into realm of the synthetic theory of evolution. In the early 1960s, biochemists Linus Pauling and Emile Zuckerkandl proposed the molecular clock hypothesis (MCH): that sequence differences between homologous proteins could be used to calculate the time since two species diverged. By 1969, Motoo Kimura and others provided a theoretical basis for the molecular clock, arguing that—at the molecular level at least—most genetic mutations are neither harmful nor helpful and that mutation and genetic drift (rather than natural selection) cause a large portion of genetic change: the neutral theory of molecular evolution. Studies of protein differences *within* species also brought molecular data to bear on population genetics by providing estimates of the level of heterozygosity in natural populations.

From the early 1960s, molecular biology was increasingly seen as a threat to the traditional core of evolutionary biology. Established evolutionary biologists—particularly Ernst Mayr, Theodosius Dobzhansky, and George Gaylord Simpson, three of the architects of the modern synthesis—were extremely skeptical of molecular approaches, especially when it came to the connection (or lack thereof) to natural selection. The molecular-clock hypothesis and the neutral theory were particularly controversial, spawning the neutralist-selectionist debate over the relative importance of mutation, drift and selection, which continued into the 1980s without a clear resolution.

Late 20th century

Gene-centered view

In the mid-1960s, George C. Williams strongly critiqued explanations of adaptations worded in terms of "survival of the species" (group selection arguments). Such explanations were largely replaced by a gene-centered view of evolution, epitomized by the kin selection arguments of W. D. Hamilton, George R. Price and John Maynard Smith. This viewpoint would be summarized and popularized in the influential 1976 book *The Selfish Gene* by Richard Dawkins. Models of the period seemed to show that group selection was severely limited in its strength; though newer models do admit the possibility of significant multi-level selection.

In 1973, Leigh Van Valen proposed the term "Red Queen," which he took from *Through the Looking-Glass* by Lewis Carroll, to describe a scenario where a species involved in one or more evolutionary arms races would have to constantly change just to keep pace with the species with which it was co-evolving. Hamilton, Williams and others suggested that this idea might explain the evolution of sexual reproduction: the increased genetic diversity caused by sexual reproduction would help maintain resistance against rapidly evolving parasites, thus making sexual reproduction common, despite the tremendous cost from the gene-centric point of view of a system where only half of an organism's genome is passed on during reproduction.

However, contrary to the expectations of the Red Queen hypothesis, Hanley *et al.* found that the prevalence, abundance and mean intensity of mites was significantly higher in sexual geckos than in asexuals sharing the same habitat. Furthermore, Parker, after reviewing numerous genetic studies on plant disease resistance, failed to find a single example consistent with the concept that pathogens are the primary selective agent responsible for sexual reproduction in their host. At an even more fundamental level, Heng and Gorelick and Heng reviewed evidence that sex, rather than enhancing diversity, acts as a constraint on genetic diversity. They considered that sex acts as a coarse filter, weeding out major genetic changes, such as chromosomal rearrangements, but permitting minor variation, such as changes at the nucleotide or gene level (that are often neutral) to pass through the sexual sieve. The adaptive function of sex, today, remains a major unresolved issue in biology. The competing models to explain the adaptive function of sex were reviewed by Birdsell and Wills. A principal alternative view to the Red Queen hypothesis is that sex arose, and is maintained, as a process for repairing DNA damage, and that genetic variation is produced as a byproduct.

The gene-centric view has also led to an increased interest in Charles Darwin's old idea of sexual selection, and more recently in topics such as sexual conflict and intragenomic conflict.

Sociobiology

W. D. Hamilton's work on kin selection contributed to the emergence of the discipline of sociobiology. The existence of altruistic behaviors has been a difficult problem for evolutionary theorists from the beginning. Significant progress was made in 1964 when Hamilton formulated the inequality in kin selection known as Hamilton's rule, which showed how eusociality in insects (the existence of sterile worker classes) and many other examples of altruistic behavior could have evolved through kin selection. Other theories followed, some derived from game theory, such as reciprocal altruism. In 1975, E. O. Wilson published the influential and highly controversial book *Sociobiology: The New Synthesis* which claimed evolutionary theory could help explain many aspects of animal, including human, behavior. Critics of sociobiology, including Stephen Jay Gould and Richard Lewontin, claimed that sociobiology greatly overstated the degree to which complex human behaviors could be determined by genetic factors. They also claimed that the theories of sociobiologists often reflected their own ideological biases. Despite these criticisms, work has continued in sociobiology and the related discipline of evolutionary psychology, including work on other aspects of the altruism problem.

Evolutionary paths and processes

One of the most prominent debates arising during the 1970s was over the theory of punctuated equilibrium. Niles Eldredge and Stephen Jay Gould proposed that there was a pattern of fossil species that remained largely unchanged for long periods (what they termed *stasis*), interspersed with relatively brief periods of rapid change during speciation. Improvements in sequencing methods resulted in a large increase of sequenced genomes, allowing the testing and refining of evolutionary theories using this huge amount of genome data. Comparisons between these genomes provide insights into the molecular mechanisms of speciation and adaptation. These genomic analyses have produced fundamental changes in the understanding of the evolutionary history of life, such as the proposal of the three-domain system by Carl Woese. Advances in computational hardware and software allow the testing and extrapolation of increasingly advanced evolutionary models and the development of the field of systems biology. One of the results has been an exchange of ideas between theories of biological evolution and the field of computer science known as evolutionary computation, which attempts to mimic biological evolution for the purpose of developing new computer algorithms. Discoveries in biotechnology now allow the modification of entire genomes, advancing evolutionary studies to the level where future experiments may involve the creation of entirely synthetic organisms.

Microbiology, horizontal gene transfer, and endosymbiosis

Microbiology was largely ignored by early evolutionary theory. This was due to the paucity of morphological traits and the lack of a species concept in microbiology, particularly amongst prokaryotes. Now, evolutionary researchers are taking advantage of their improved understanding of microbial physiology and ecology, produced by the comparative ease of microbial genomics, to explore the taxonomy and evolution of these organisms. These studies are revealing unanticipated levels of diversity amongst microbes.

One important development in the study of microbial evolution came with the discovery in Japan in 1959 of horizontal gene transfer. This transfer of genetic material between different species of bacteria came to the attention of scientists because it played a major role in the spread of antibiotic resistance. More recently, as knowledge of genomes has continued to expand, it has been suggested that lateral transfer of genetic material has played an important role in the evolution of all organisms. These high levels of horizontal gene transfer have led to suggestions that the family tree of today's organisms, the so-called "tree of life," is more similar to an interconnected web or net.

Indeed, the endosymbiotic theory for the origin of organelles sees a form of horizontal gene transfer as a critical step in the evolution of eukaryotes such as fungi, plants, and animals. The endosymbiotic theory holds that organelles within the cells of eukorytes such as mitochondria and chloroplasts, had descended from independent bacteria that came to live symbiotically within other cells. It had been suggested in the late 19th century when similarities between mitochondria and bacteria were noted, but largely dismissed until it was revived and championed by Lynn Margulis in the 1960s and 1970s; Margulis was able to make use of new evidence that such organelles had their own DNA that was inherited independently from that in the cell's nucleus.

From spandrels to evolutionary developmental biology

In the 1980s and 1990s, the tenets of the modern evolutionary synthesis came under increasing scrutiny. There was a renewal of structuralist themes in evolutionary biology in the work of biologists such as Brian Goodwin and Stuart Kauffman, which incorporated ideas from cybernetics and systems theory, and emphasized the self-organizing processes of development as factors directing the course of evolution. The evolutionary biologist Stephen Jay Gould revived earlier ideas of heterochrony, alterations in the relative rates of developmental processes over the course of evolution, to account for the generation of novel forms, and, with the evolutionary biologist Richard Lewontin, wrote an influential paper in 1979 suggesting that a change in one biological structure, or even a structural novelty, could arise incidentally as an accidental result of selection on another structure, rather than through direct selection for that particular adaptation. They called such incidental structural changes "spandrels" after an architectural feature. Later, Gould and Elisabeth Vrba discussed the acquisition of new functions by novel structures arising in this fashion, calling them "exaptations."

Molecular data regarding the mechanisms underlying development accumulated rapidly during the 1980s and 1990s. It became clear that the diversity of animal morphology was not the result of different sets of proteins regulating the development of different animals, but from changes in the deployment of a small set of proteins that were common to all animals. These proteins became known as the "developmental-genetic toolkit." Such perspectives influenced the disciplines of phylogenetics, paleontology and comparative developmental biology, and spawned the new discipline of evolutionary developmental biology also known as evo-devo.

21st century

Macroevolution and microevolution

One of the tenets of population genetics since its inception has been that macroevolution (the evolution of phylogenic clades at the species level and above) was solely the result of the mechanisms of microevolution (changes in gene frequency within populations) operating over an extended period of time. During the last decades of the 20th century some paleontologists raised questions about whether other factors, such as punctuated equilibrium and group selection operating on the level of entire species and even higher level phylogenic clades, needed to be considered to explain patterns in evolution revealed by statistical analysis of the fossil record. Near the end of the 20th century some researchers in evolutionary developmental biology suggested that interactions between the environment and the developmental process might have been the source of some of the structural innovations seen in macroevolution, but other evo-devo researchers maintained that genetic mechanisms visible at the population level are fully sufficient to explain all macroevolution.

Epigenetic inheritance

Epigenetics is the study of heritable changes in gene expression or cellular phenotype caused by mechanisms other than changes in the underlying DNA sequence. By the first decade of the 21st century it had become accepted that epigenetic mechanisms were a necessary part of the evolutionary origin of cellular differentiation. Although epigenetics in multicellular organisms is generally thought to be a mechanism involved in differentiation, with epigenetic patterns "reset" when organisms reproduce, there have been some observations of transgenerational epigenetic inheritance. This shows that in some cases nongenetic changes to an organism can be inherited and it has been suggested that such inheritance can help with adaptation to local conditions and affect evolution. Some have suggested that in certain cases a form of Lamarckian evolution may occur.

Extended evolutionary syntheses

The idea of an extended evolutionary synthesis is to extend the 20th century modern synthesis to include concepts and mechanisms such as multilevel selection theory, transgenerational epigenetic inheritance, niche construction and evolvability—though several different such syntheses have been proposed, with no agreement on what exactly would be included.

Unconventional evolutionary theory

Omega Point

Pierre Teilhard de Chardin's metaphysical Omega Point theory, found in his book *The Phenomenon of Man* (1955), describes the gradual development of the universe from subatomic particles to human society, which he viewed as its final stage and goal, a form of orthogenesis.

Gaia hypothesis

The Gaia hypothesis proposed by James Lovelock holds that the living and nonliving parts of Earth can be viewed as a complex interacting system with similarities to a single organism, as being connected to Lovelock's ideas. The Gaia hypothesis has also been viewed by Lynn Margulis and others as an extension of endosymbiosis and exosymbiosis. This modified hypothesis postulates that all living things have a regulatory effect on the Earth's environment that promotes life overall.

Self-organization

The mathematical biologist Stuart Kauffman has suggested that self-organization may play roles alongside natural selection in three areas of evolutionary biology, namely population dynamics, molecular evolution, and morphogenesis. However, Kauffman does not take into account the essential role of energy (for example, using pyrophosphate) in driving biochemical reactions in cells, as proposed by Christian DeDuve and modelled mathematically by Richard Bagley and Walter Fontana. Their systems are self-catalyzing but not simply self-organizing as they are thermodynamically open systems relying on a continuous input of energy.

Chapter 35

History of Geophysics

The **historical development of geophysics** has been motivated by two factors. One of these is the research curiosity of humankind related to planet Earth and its several components, its events and its problems. The second is economical usage of Earth's resources (ore deposits, petroleum, water resources, etc.) and Earth-related hazards such as earthquakes, volcanoes, tsunamis, tides, and floods.

Classical and observational period

In circa 240 BC, Eratosthenes of Cyrene measured the circumference of Earth using geometry and the angle of the Sun at more than one latitude in Egypt.

There is some information about earthquakes in Aristotle's *Meteorology*, in *Naturalis Historia* by Pliny the Elder, and in Strabo's *Geographica*. Aristotle and Strabo recorded observations on tides.

A natural explanation of volcanoes was first undertaken by the Greek philosopher Empedocles (c. 490-430 B.C.), who considered the world to be divided into four elemental forces: earth, air, fire and water. He maintained that volcanoes were manifestation of elemental fire. Winds and earthquakes would play a key role in explanations of volcanoes. Lucretius claimed Mount Etna was completely hollow and the fires of the underground driven by a fierce wind circulating near sea level. Pliny the Elder noted that the presence of earthquakes preceded an eruption. Athanasius Kircher (1602–1680) witnessed eruptions of Mount Etna and Stromboli, then visited the crater of Vesuvius and published his view of an Earth with a central fire connected to numerous others caused by the burning of sulfur, bitumen and coal.

Instrumental and analytical period

Arguably the first modern experimental treatise was William Gilbert's *De Magnete* (1600), in which he deduced that compasses point north because the Earth itself is magnetic. In 1687 Isaac Newton published his *Principia*, which not only laid the foundations for classical mechanics and gravitation but also explained a variety of geophysical phenomena such as tides and the precession of the equinox.

These experimental and mathematical analyses were applied to several areas of geophysics: Earth's shape, density, and gravity field (Pierre Bouguer, Alexis Clairaut and Henry Cavendish), Earth's magnetic field (Alexander von Humboldt, Edmund Halley and Carl Friedrich Gauss), seismology (John Milne and Robert Mallet), and the Earth's age, heat and radioactivity (Arthur Holmes and William Thomson, 1st Baron Kelvin).

There are several descriptions and discussions about a philosophical theory of the water cycle by Marcus Vitruvius, Leonardo da Vinci and Bernard Palissy. Pioneers in hydrology include Pierre Perrault, Edme Mariotte and Edmund Halley in studies of such things as rainfall, runoff, drainage area, velocity, river cross-section measurements and discharge. Advances in the 18th century included Daniel Bernoulli's piezometer and Bernoulli's equation as well as the Pitot tube by Henri Pitot. In the 19th century, groundwater hydrology was furthered by Darcy's law, the Dupuit-Thiem well formula, and the Hagen-Poiseuille equation for flows through pipes. *Physical Geography of the Sea*, the first textbook of oceanography, was written by Matthew Fontaine Maury in 1855.

The thermoscope, or Galileo thermometer, was constructed by Galileo Galilei in 1607. In 1643, Evangelista Torricelli invented the mercury barometer. Blaise Pascal (in 1648) rediscovered that atmospheric pressure decreases with height, and deduced that there is a vacuum above the atmosphere.

Emergence as a discipline

The first known use of the word *geophysics* was by Julius Fröbel in 1834 (in German). It was used occasionally in the next few decades, but did not catch on until journals devoted to the subject began to appear, beginning with *Beiträge zur Geophysik* in 1887. The future *Journal of Geophysical Research* was founded in 1896 with the title *Terrestrial Magnetism*. In 1898, a Geophysical Institute was founded at the University of Göttingen, and Emil Wiechert became the world's first Chair of Geophysics. An international framework for geophysics was provided by the founding of the International Union of Geodesy and Geophysics in 1919.

20th century

The 20th century was a revolutionary age for geophysics. As an international scientific effort between 1957 and 1958, the International Geophysical Year or IGY was one of the most important for scientific activity of all disciplines of geophysics: aurora and airglow, cosmic rays, geomagnetism, gravity, ionospheric physics, longitude and latitude determinations (precision mapping), meteorology, oceanography, seismology and solar activity.

Earth's interior and seismology

Determining the physics of Earth's interior was enabled by the development of the first seismographs in the 1880s. Based on the behavior of the waves reflected off the internal layers of the Earth, several theories developed as to what would cause variances in wave speed or loss of certain frequencies. This led to scientists like Inge Lehmann discovering the presence of the Earth's core in 1936. Beno Gutenberg and Harold Jeffreys worked at explaining the difference in Earth's density due to compression and the shear velocity of waves. Since seismology is based on elastic waves, the speed of waves could help determine density and therefore the behavior of the layers within the Earth.

Nomenclature for the behavior of seismic waves was produced based on these findings. P-waves and S-waves were used to describe two types of elastic body waves possible. Love waves and Rayleigh waves were used to describe two types of surface waves possible.

Scientists who have contributed to advances in knowledge about the Earth's interior and seismology include Emil Wiechert, Beno Gutenberg, Andrija Mohorovičić, Harold Jeffreys, Inge Lehmann, Edward Bullard, Charles Francis Richter, Francis Birch, Frank Press, Hiroo Kanamori and Walter Elsasser.

One highly debated topic about Earth's interior is mantle plumes. These are theorized to be rising magma, which is responsible for the hotspots in the world, like Hawaii. Originally the theory was that mantle plumes rose up in a direct path, but now there is evidence that the plumes may deflect by small degrees as they rise. It was also found that the proposed hotspot underneath Yellowstone may not be related to a rising mantle plume. This theory has not been fully researched.

Plate tectonics

In the second half of the 20th century, plate tectonics theory was developed by several contributors including Alfred Wegener, Maurice Ewing, Robert S. Dietz, Harry Hammond Hess, Hugo Benioff, Walter C. Pitman, III, Frederick Vine, Drummond Matthews, Keith Runcorn, Bryan L. Isacks, Edward Bullard, Xavier Le Pichon, Dan McKenzie, W. Jason Morgan and John Tuzo Wilson. Prior to this, people had ideas of continental drift, but no real evidence came until the late 20th century. Alexander von Humboldt observed in the early 19th century the geometry and geology of the shores of continents of the Atlantic Ocean. James Hutton and Charles Lyell brought about the idea of gradual change, uniformitarianism, which helped people cope with the slow drift of the continents. Alfred Wegener spearheaded the original theory of continental drift and spent much of his life devoted to this theory. He proposed "Pangaea", one unified giant continent.

During the development of continental drift theory, there was not much exploration of the oceanic part of the world, only continental. Once people began to pay attention to the ocean, geologists found that the floor was spreading, and in different rates at different spots. There are three different main ways in which plates can move: transform, divergent, and Convergent. As well, there can be Rifts, areas where the land is beginning to spread apart.

Oceanography

Advances in physical oceanography occurred in the 20th century. Sea depth by acoustic measurements was first made in 1914. The German "Meteor" expedition gathered 70,000 ocean depth measurements using an echo sounder, surveying the Mid-Atlantic Ridge between 1925 and 1927. The Great Global Rift was discovered by Maurice Ewing and Bruce Heezen in 1953, and the mountain range under the Arctic was found in 1954 by the Arctic Institute of the USSR. The theory of seafloor spreading was developed in 1960 by Harry Hammond Hess. The Ocean Drilling Program started in 1966. There has been much emphasis on the application of large scale computers to oceanography to allow numerical predictions of ocean conditions and as a part of overall environmental change prediction.

Geomagnetism

The motion of the conductive molten metal beneath the Earth's crust, or the Earth's dynamo, is responsible for the existence of the magnetic field. The interaction of the magnetic field and solar radiation has an impact on how much radiation reaches the surface of Earth and the integrity of the atmosphere. It has been found that the magnetic poles of the Earth have reversed several times, allowing researchers to get an idea of the surface conditions of the planet at that time. The cause of the magnetic poles being reversed is unknown, and the intervals of change vary and do not show a consistent interval. It is believed that the reversal is correlated to the Earth's mantle, although exactly how is still debated.

Distortions to the Earth's magnetic field cause the phenomenon Aurora Borealis, commonly called the Northern Lights. The magnetic field stores energy given by cosmic particles known as solar wind, which causes the magnetic field lines to expand. When the lines contract, they release this energy, which can be seen as the Northern Lights.

Atmospheric influences

The Earth's climate changes over time due to the planet's atmospheric composition, the sun's luminosity, and the occurrence of catastrophic events.

Atmospheric composition affects and is affected by the biological mechanisms active on the Earth's surface. Organisms effect the amount of oxygen vs. carbon dioxide through respiration and photosynthesis. They also affect the levels of nitrogen through fixation, nitrification, and denitrification. The ocean is capable of absorbing carbon dioxide from the atmosphere, but this varies based on the levels of nitrogen and phosphorus present in the water. Humans have also played a role in changing the atmospheric composition of the Earth through industrial byproducts, deforestation, and motor vehicles.

The luminosity of the Sun increases as it progresses through its life cycle and are visible over the course of millions of years. Sunspots can form on the Sun's surface, which can cause greater variability in the emissions that Earth receives.

Volcanoes form when two plates meet and one subducts underneath the other. They thus form along most plate boundaries; the Ring of Fire is an example of this. The study of volcanoes along plate boundaries has shown a correlation between eruptions and climate. Alan Robock theorizes that volcanic activity can influence climate and can lead to global cooling for years. The leading idea, based on volcanic eruptions, is that sulfur dioxide released from volcanoes has a major effect on the cooling of the atmosphere following the eruption.

Impacts from large celestial bodies, commonly asteroids, create shock waves that push air and distribute dust into the atmosphere, blocking sunlight. This causes global cooling, which can lead to the death and possible extinction of many species.

Industrial application

Industrial applications of geophysics were developed by demand of petroleum exploration and recovery in the 1920s. Later, petroleum, mining and groundwater geophysics were improved. Earthquake hazard minimization and soil/site investigations for earthquake-prone areas were new applications of geophysical engineering in the 1990s.

Seismology is used in the mining industry to read and build models of events that may have been caused or contributed to by the process of mining. This allows scientists to predict the hazards associated with mining in the area.

Much like mining, seismic waves are used to create models of the Earth's subsurface. Geological features, called traps, that commonly indicate the presence of oil, can be identified from the model and used to determine suitable sites to drill.

Groundwater is highly vulnerable to the pollution produced from industry and waste disposal. In order to preserve the quality of fresh water sources, maps of groundwater depth are created and compared to the locations of pollutant sources.

Chapter 36

History of Paleontology

The **history of paleontology** traces the history of the effort to understand the history of life on Earth by studying the fossil record left behind by living organisms. Since it is concerned with understanding living organisms of the past, paleontology can be considered to be a field of biology, but its historical development has been closely tied to geology and the effort to understand the history of Earth itself.

In ancient times, Xenophanes (570–480 BC), Herodotus (484–425 BC), Eratosthenes (276–194 BC), and Strabo (64 BC-24 AD) wrote about fossils of marine organisms, indicating that land was once under water. The ancient Chinese considered them to be dragon bones and documented them as such. During the Middle Ages, fossils were discussed by Persian naturalist Ibn Sina (known as *Avicenna* in Europe) in *The Book of Healing* (1027), which proposed a theory of petrifying fluids that Albert of Saxony would elaborate on in the 14th century. The Chinese naturalist Shen Kuo (1031–1095) would propose a theory of climate change based on evidence from petrified bamboo.

In early modern Europe, the systematic study of fossils emerged as an integral part of the changes in natural philosophy that occurred during the Age of Reason. The nature of fossils and their relationship to life in the past became better understood during the 17th and 18th centuries, and at the end of the 18th century, the work of Georges Cuvier had ended a long running debate about the reality of extinction, leading to the emergence of paleontology – in association with comparative anatomy – as a scientific discipline. The expanding knowledge of the fossil record also played an increasing role in the development of geology, and stratigraphy in particular.

In 1822, the word "paleontology" was used by the editor of a French scientific journal to refer to the study of ancient living organisms through fossils, and the first half of the 19th century saw geological and paleontological activity become increasingly well organized with the growth of geologic societies and museums and an increasing number of professional geologists and fossil specialists. This contributed to a rapid increase in knowledge about the history of life on Earth, and progress towards definition of the geologic time scale largely based on fossil evidence. As knowledge of life's history continued to improve, it became increasingly obvious that there had been some kind of successive order to the development of life. This would encourage early evolutionary theories on the transmutation of species. After Charles Darwin published *Origin of Species* in 1859, much of the focus of paleontology shifted to understanding evolutionary paths, including human evolution, and evolutionary theory.

The last half of the 19th century saw a tremendous expansion in paleontological activity, especially in North America. The trend continued in the 20th century with additional regions of the Earth being opened to systematic fossil collection, as demonstrated by a series of important discoveries in China near the end of the 20th century. Many transitional fossils have been discovered, and there is now considered to be abundant evidence of how all classes of vertebrates are related, much of it in the form of transitional fossils. The last few decades of the 20th century saw a renewed interest in mass extinctions and their role in the evolution of life on Earth. There was also a renewed interest in the Cambrian explosion that saw the development of the body plans of most animal phyla. The discovery of fossils of the Ediacaran biota and developments in paleobiology extended knowledge about the history of life back far before the Cambrian.

Prior to the 17th century

As early as the 6th century BC, the Greek philosopher Xenophanes of Colophon (570–480 BC) recognized that some fossil shells were remains of shellfish, which he used to argue that what was at the time dry land was once under the sea. Leonardo da Vinci (1452–1519), in an unpublished notebook, also concluded that some fossil sea shells were the remains of shellfish. However, in both cases, the fossils were complete remains of shellfish species that closely resembled living species, and were therefore easy to classify.

In 1027, the Persian naturalist, Ibn Sina (known as *Avicenna* in Europe), proposed an explanation of how the stoniness of fossils was caused in *The Book of Healing*. He modified an idea of Aristotle's, which explained it in terms of vaporous exhalations. Ibn Sina modified this into the theory of petrifying fluids (*succus lapidificatus*), which was elaborated on by Albert of Saxony in the 14th century and was accepted in some form by most naturalists by the 16th century.

Shen Kuo (Chinese:) (1031–1095) of the Song Dynasty used marine fossils found in the Taihang Mountains to infer the existence of geological processes such as geomorphology and the shifting of seashores over time. Using his observation of preserved petrified bamboos found underground in Yan'an, Shanbei region, Shaanxi province, he argued for a theory of gradual climate change, since Shaanxi was part of a dry climate zone that did not support a habitat for the growth of bamboos.

As a result of a new emphasis on observing, classifying, and cataloging nature, 16th-century natural philosophers in Europe began to establish extensive collections of fossil objects (as well as collections of plant and animal specimens), which were often stored in specially built cabinets to help organize them. Conrad Gesner published a 1565 work on fossils that contained one of the first detailed descriptions of such a cabinet and collection. The collection belonged to a member of the extensive network of correspondents that Gesner drew on for his works. Such informal correspondence networks among natural philosophers and collectors became increasingly important during the course of the 16th century and were direct forerunners of the scientific societies that would begin to form in the 17th century. These cabinet collections and correspondence networks played an important role in the development of natural philosophy.

However, most 16th-century Europeans did not recognize that fossils were the remains of living organisms. The etymology of the word *fossil* comes from the Latin for things having been dug up. As this indicates, the term was applied to a wide variety of stone and stone-like objects without regard to whether they might have an organic origin. 16th-century writers such as Gesner and Georg Agricola were more interested in classifying such objects by their physical and mystical properties than they were in determining the objects' origins. In addition, the natural philosophy of the period encouraged alternative explanations for the origin of fossils. Both the Aristotelian and Neoplatonic schools of philosophy provided support for the idea that stony objects might grow within the earth to resemble living things. Neoplatonic philosophy maintained that there could be affinities between living and non-living objects that could cause one to resemble the other. The Aristotelian school maintained that the seeds of living organisms could enter the ground and generate objects resembling those organisms.

Leonardo da Vinci and the development of paleontology

Leonardo da Vinci established a line of continuity between the two main branches of paleontology: body fossil palaeontology and ichnology. In fact, Leonardo dealt with both major classes of fossils: (1) body fossils, e.g. fossilized shells; (2) ichnofossils (also known as trace fossils), i.e. the fossilized products of life-substrate interactions (e.g. burrows and borings). In folios 8 to 10 of the Leicester code, Leonardo examined the subject of body fossils, tackling one of the vexing issues of his contemporaries: why do we find petrified seashells on mountains? Leonardo answered this question by correctly interpreting the biogenic nature of fossil mollusks and their sedimentary matrix. The interpretation of Leonardo da Vinci appears extraordinarily innovative as he surpassed three centuries of scientific debate on the nature of body fossils. Da Vinci took into consideration invertebrate ichnofossils to prove his ideas on the nature of fossil objects. To da Vinci, ichnofossils played a central role in demonstrating: (1) the organic nature of petrified shells and (2) the sedimentary origin of the rock layers bearing fossil objects. Da Vinci described what are bioerosion ichnofossils:

“The hills around Parma and Piacenza show abundant mollusks and bored corals still attached to the rocks. When I was working on the great horse in Milan, certain peasants brought me a huge bagful of them”

- Leicester Code, folio 9r

Such fossil borings allowed Leonardo to confute the Inorganic theory, i.e. the idea that so-called petrified shells (mollusk body fossils) are inorganic curiosities. With the words of Leonardo da Vinci:

“[the Inorganic theory is not true] because there remains the trace of the [animal’s] movements on the shell which [it] consumed in the same manner of a woodworm in wood ...”

- Leicester Code, folio 9v

Da Vinci discussed not only fossil borings, but also burrows. Leonardo used fossil burrows as paleoenvironmental tools to demonstrate the marine nature of sedimentary strata:

“Between one layer and the other there remain traces of the worms that crept between them when they had not yet dried.

All the sea mud still contains shells, and the shells are petrified together with the mud’’

- Leicester Code, folio 10v

Other Renaissance naturalists studied invertebrate ichnofossils during the Renaissance, but none of them reached such accurate conclusions. Leonardo's considerations of invertebrate ichnofossils are extraordinarily modern not only when compared to those of his contemporaries, but also to interpretations in later times. In fact, during the 1800s invertebrate ichnofossils were explained as fucoids, or seaweed, and their true nature was widely understood only by the early 1900s. For these reasons, Leonardo da Vinci is deservedly considered the founding father of both the major branches of palaeontology, i.e. the study of body fossils and ichnology.

17th century

During the Age of Reason, fundamental changes in natural philosophy were reflected in the analysis of fossils. In 1665 Athanasius Kircher attributed giant bones to extinct races of giant humans in his *Mundus subterraneus*. In the same year Robert Hooke published *Micrographia*, an illustrated collection of his observations with a microscope. One of these observations was entitled "Of Petrify'd wood, and other Petrify'd bodies", which included a comparison between petrified and ordinary wood. He concluded that petrified wood was ordinary wood that had been soaked with "water impregnated with stony and earthy particles". He then suggested that several kinds of fossil sea shells were formed from ordinary shells by a similar process. He argued against the prevalent view that such objects were "Stones form'd by some extraordinary Plastick virtue latent in the Earth itself". Hooke believed that fossils provided evidence about the history of life on Earth writing in 1668:

> ...if the finding of Coines, Medals, Urnes, and other Monuments of famous persons, or Towns, or Utensils, be admitted for unquestionable Proofs, that such Persons or things have, in former times had a being, certainly those Petrifactions may be allowed to be of equal Validity and Evidence, that there have formerly been such Vegetables or Animals... and are true universal Characters legible to all rational Men.

Hooke was prepared to accept the possibility that some such fossils represented species that had become extinct, possibly in past geological catastrophes.

In 1667 Nicholas Steno wrote a paper about a shark head he had dissected. He compared the teeth of the shark with the common fossil objects known as "tongue stones" or *glossopetrae*. He concluded that the fossils must have been shark teeth. Steno then took an interest in the question of fossils, and to address some of the objections to their organic origin he began studying rock strata. The result of this work was published in 1669 as *Forerunner to a Dissertation on a solid naturally enclosed in a solid*. In this book, Steno drew a clear distinction between objects such as rock crystals that really were formed within rocks and those such as fossil shells and shark teeth that were formed outside of those rocks. Steno realized that certain kinds of rock had been formed by the successive deposition of horizontal layers of sediment and that fossils were the remains of living organisms that had become buried in that sediment. Steno who, like almost all 17th-century natural philosophers, believed that the earth was only a few thousand years old, resorted to the Biblical flood as a possible explanation for fossils of marine organisms that were far from the sea.

Despite the considerable influence of *Forerunner*, naturalists such as Martin Lister (1638–1712) and John Ray (1627–1705) continued to question the organic origin of some fossils. They were particularly concerned about objects such as fossil Ammonites, which Hooke claimed were organic in origin, that did not resemble any known living species. This raised the possibility of extinction, which they found difficult to accept for philosophical and theological reasons. In 1695 Ray wrote to the Welsh naturalist Edward Lluyd complaining of such views: "... there follows such a train of consequences, as seem to shock the Scripture-History of the novity of the World; at least they overthrow the opinion received, & not without good reason, among Divines and Philosophers, that since the first Creation there have been no species of Animals or Vegetables lost, no new ones produced."

18th century

In his 1778 work *Epochs of Nature* Georges Buffon referred to fossils, in particular the discovery of fossils of tropical species such as elephants and rhinoceros in northern Europe, as evidence for the theory that the earth had started out much warmer than it currently was and had been gradually cooling.

In 1796 Georges Cuvier presented a paper on living and fossil elephants comparing skeletal remains of Indian and African elephants to fossils of mammoths and of an animal he would later name mastodon utilizing comparative anatomy. He established for the first time that Indian and African elephants were different species, and that mammoths differed from both and must be extinct. He further concluded that the mastodon was another extinct species that also differed from Indian or African elephants, more so than mammoths. Cuvier made another powerful demonstration of the power of comparative anatomy in paleontology when he presented a second paper in 1796 on a large fossil skeleton from Paraguay, which he named *Megatherium* and identified as a giant sloth by comparing its skull to those of two living species of tree sloth. Cuvier's ground-breaking work in paleontology and comparative anatomy led to the widespread acceptance of extinction. It also led Cuvier to advocate the geological theory of catastrophism to explain the succession of organisms revealed by the fossil record. He also pointed out that since mammoths and woolly rhinoceros were not the same species as the elephants and rhinoceros currently living in the tropics, their fossils could not be used as evidence for a cooling earth.

In a pioneering application of stratigraphy, William Smith, a surveyor and mining engineer, made extensive use of fossils to help correlate rock strata in different locations. He created the first geological map of England during the late 1790s and early 19th century. He established the principle of faunal succession, the idea that each strata of sedimentary rock would contain particular types of fossils, and that these would succeed one another in a predictable way even in widely separated geologic formations. At the same time, Cuvier and Alexandre Brongniart, an instructor at the Paris school of mine engineering, used similar methods in an influential study of the geology of the region around Paris.

Early to mid-19th century

The study of fossils and the origin of the word *paleontology*

The Smithsonian Libraries consider that the first edition of a work which laid the foundation to vertebrate paleontology was Georges Cuvier's *Recherches sur les ossements fossiles de quadrupèdes* (*Researches on quadruped fossil bones*), published in France in 1812. Referring to the second edition of this work (1821), Cuvier's disciple and editor of the scientific publication *Journal de physique* Henri Marie Ducrotay de Blainville published in January 1822, in the *Journal de physique*, an article titled "Analyse des principaux travaux dans les sciences physiques, publiés dans l'année 1821" ("Analysis of the main works in the physical sciences, published in the year 1821"). In this article Blainville unveiled for the first time the printed word *palæontologie* which later gave the English word "paleontology". Blainville had already coined the term *paléozoologie* in 1817 to refer to the work Cuvier and others were doing to reconstruct extinct animals from fossil bones. However, Blainville began looking for a term that could refer to the study of both fossil animal and plant remains. After trying some unsuccessful alternatives, he hit on "palaeontologie" in 1822. Blainville's term for the study of the fossilized organisms quickly became popular and was anglicized into "paleontology".

In 1828 Alexandre Brongniart's son, the botanist Adolphe Brongniart, published the introduction to a longer work on the history of fossil plants. Adolphe Brongniart concluded that the history of plants could roughly be divided into four parts. The first period was characterized by cryptogams. The second period was characterized by the appearance of the conifers. The third period brought emergence of the cycads, and the fourth by the development of the flowering plants (such as the dicotyledons). The transitions between each of these periods was marked by sharp discontinuities in the fossil record, with more gradual changes within the periods. Brongniart's work is the foundation of paleobotany and reinforced the theory that life on earth had a long and complex history, and different groups of plants and animals made their appearances in successive order. It also supported the idea that the Earth's climate had changed over time as Brongniart concluded that plant fossils showed that during the Carboniferous the climate of Northern Europe must have been tropical. The term "paleobotany" was coined in 1884 and "palynology" in 1944.

The age of reptiles

In 1808, Cuvier identified a fossil found in Maastricht as a giant marine reptile that would later be named *Mosasaurus*. He also identified, from a drawing, another fossil found in Bavaria as a flying reptile and named it *Pterodactylus*. He speculated, based on the strata in which these fossils were found, that large reptiles had lived prior to what he was calling "the age of mammals". Cuvier's speculation would be supported by a series of finds that would be made in Great Britain over the course of the next two decades. Mary Anning, a professional fossil collector since age eleven, collected the fossils of a number of marine reptiles and prehistoric fish from the Jurassic marine strata at Lyme Regis. These included the first ichthyosaur skeleton to be recognized as such, which was collected in 1811, and the first two plesiosaur skeletons ever found in 1821 and 1823. Mary Anning was only 12 when she and her brother discovered the Ichthyosaurus skeleton. Many of her discoveries would be described scientifically by the geologists William Conybeare, Henry De la Beche, and William Buckland. It was Anning who observed that stony objects known as "bezoar stones" were often found in the abdominal region of ichthyosaur skeletons, and she noted that if such stones were broken open they often contained fossilized fish bones and scales as well as sometimes bones from small ichthyosaurs. This led her to suggest to Buckland that they were fossilized feces, which he named coprolites, and which he used to better understand ancient food chains. Mary Anning made many fossil discoveries that revolutionized science. However, despite her phenomenal scientific contributions, she was rarely recognized officially for her discoveries. Her discoveries were often credited to wealthy men who bought her fossils.

In 1824, Buckland found and described a lower jaw from Jurassic deposits from Stonesfield. He determined that the bone belonged to a carnivorous land-dwelling reptile he called *Megalosaurus*. That same year Gideon Mantell realized that some large teeth he had found in 1822, in Cretaceous rocks from Tilgate, belonged to a giant herbivorous land-dwelling reptile. He called it *Iguanodon*, because the teeth resembled those of an iguana. All of this led Mantell to publish an influential paper in 1831 entitled "The Age of Reptiles" in which he summarized the evidence for there having been an extended time during which the earth had teemed with large reptiles, and he divided that era, based in what rock strata different types of reptiles first appeared, into three intervals that anticipated the modern periods of the Triassic, Jurassic, and Cretaceous. In 1832 Mantell would find, in Tilgate, a partial skeleton of an armored reptile he would call *Hylaeosaurus*. In 1841 the English anatomist Richard Owen would create a new order of reptiles, which he called Dinosauria, for *Megalosaurus*, *Iguanodon*, and *Hylaeosaurus*.

This evidence that giant reptiles had lived on Earth in the past caused great excitement in scientific circles, and even among some segments of the general public. Buckland did describe the jaw of a small primitive mammal, *Phascolotherium*, that was found in the same strata as *Megalosaurus*. This discovery, known as the Stonesfield mammal, was a much discussed anomaly. Cuvier at first thought it was a marsupial, but Buckland later realized it was a primitive placental mammal. Due to its small size and primitive nature, Buckland did not believe it invalidated the overall pattern of an age of reptiles, when the largest and most conspicuous animals had been reptiles rather than mammals.

Catastrophism, uniformitarianism and the fossil record

In Cuvier's landmark 1796 paper on living and fossil elephants, he referred to a single catastrophe that destroyed life to be replaced by the current forms. As a result of his studies of extinct mammals, he realized that animals such as *Palaeotherium* had lived before the time of the mammoths, which led him to write in terms of multiple geological catastrophes that had wiped out a series of successive faunas. By 1830, a scientific consensus had formed around his ideas as a result of paleobotany and the dinosaur and marine reptile discoveries in Britain. In Great Britain, where natural theology was very influential in the early 19th century, a group of geologists that included Buckland, and Robert Jameson insisted on explicitly linking the most recent of Cuvier's catastrophes to the biblical flood. Catastrophism had a religious overtone in Britain that was absent elsewhere.

Partly in response to what he saw as unsound and unscientific speculations by William Buckland and other practitioners of flood geology, Charles Lyell advocated the geological theory of uniformitarianism in his influential work *Principles of Geology*. Lyell amassed evidence, both from his own field research and the work of others, that most geological features could be explained by the slow action of present-day forces, such as vulcanism, earthquakes, erosion, and sedimentation rather than past catastrophic events. Lyell also claimed that the apparent evidence for catastrophic changes in the fossil record, and even the appearance of directional succession in the history of life, were illusions caused by imperfections in that record. For instance he argued that the absence of birds and mammals from the earliest fossil strata was merely an imperfection in the fossil record attributable to the fact that marine organisms were more easily fossilized. Also Lyell pointed to the Stonesfield mammal as evidence that mammals had not necessarily been preceded by reptiles, and to the fact that certain Pleistocene strata showed a mixture of extinct and still surviving species, which he said showed that extinction occurred piecemeal rather than as a result of catastrophic events. Lyell was successful in convincing geologists of the idea that the geological features of the earth were largely due to the action of the same geologic forces that could be observed in the present day, acting over an extended period of time. He was not successful in gaining support for his view of the fossil record, which he believed did not support a theory of directional succession.

Transmutation of species and the fossil record

- In the early 19th century Jean Baptiste Lamarck used fossils to argue for his theory of the transmutation of species. Fossil finds, and the emerging evidence that life had changed over time, fueled speculation on this topic during the next few decades. Robert Chambers used fossil evidence in his 1844 popular science book *Vestiges of the Natural History of Creation*, which advocated an evolutionary origin for the cosmos as well as for life on earth. Like Lamarck's theory it maintained that life had progressed from the simple to the complex.

These early evolutionary ideas were widely discussed in scientific circles but were not accepted into the scientific mainstream. Many of the critics of transmutational ideas used fossil evidence in their arguments. In the same paper that coined the term dinosaur Richard Owen pointed out that dinosaurs were at least as sophisticated and complex as modern reptiles, which he claimed contradicted transmutational theories. Hugh Miller would make a similar argument, pointing out that the fossil fish found in the Old Red Sandstone formation were fully as complex as any later fish, and not the primitive forms alleged by *Vestiges*. While these early evolutionary theories failed to become accepted as mainstream science, the debates over them would help pave the way for the acceptance of Darwin's theory of evolution by natural selection a few years later.

Geological time scale and the history of life

Geologists such as Adam Sedgwick, and Roderick Murchison continued, in the course of disputes such as The Great Devonian Controversy, to make advances in stratigraphy. They described newly recognized geological periods, such as the Cambrian, the Silurian, the Devonian, and the Permian. Increasingly, such progress in stratigraphy depended on the opinions of experts with specialized knowledge of particular types of fossils such as William Lonsdale (fossil corals), and John Lindley (fossil plants) who both played a role in the

Devonian controversy and its resolution. By the early 1840s much of the geologic time scale had been developed. In 1841, John Phillips formally divided the geologic column into three major eras, the Paleozoic, Mesozoic, and Cenozoic, based on sharp breaks in the fossil record. He identified the three periods of the Mesozoic era and all the periods of the Paleozoic era except the Ordovician. His definition of the geological time scale is still used today. It remained a relative time scale with no method of assigning any of the periods' absolute dates. It was understood that not only had there been an "age of reptiles" preceding the current "age of mammals", but there had been a time (during the Cambrian and the Silurian) when life had been restricted to the sea, and a time (prior to the Devonian) when invertebrates had been the largest and most complex forms of animal life.

Expansion and professionalization of geology and paleontology

This rapid progress in geology and paleontology during the 1830s and 1840s was aided by a growing international network of geologists and fossil specialists whose work was organized and reviewed by an increasing number of geological societies. Many of these geologists and paleontologists were now paid professionals working for universities, museums and government geological surveys. The relatively high level of public support for the earth sciences was due to their cultural impact, and their proven economic value in helping to exploit mineral resources such as coal.

Another important factor was the development in the late 18th and early 19th centuries of museums with large natural history collections. These museums received specimens from collectors around the world and served as centers for the study of comparative anatomy and morphology. These disciplines played key roles in the development of a more technically sophisticated form of natural history. One of the first and most important examples was the Museum of Natural History in Paris, which was at the center of many of the developments in natural history during the first decades of the 19th century. It was founded in 1793 by an act of the French National Assembly, and was based on an extensive royal collection plus the private collections of aristocrats confiscated during the French revolution, and expanded by material seized in French military conquests during the Napoleonic Wars. The Paris museum was the professional base for Cuvier, and his professional rival Geoffroy Saint-Hilaire. The English anatomists Robert Grant and Richard Owen both spent time studying there. Owen would go on to become the leading British morphologist while working at the museum of the Royal College of Surgeons.

Late 19th century

Evolution

Charles Darwin's publication of the *On the Origin of Species* in 1859 was a watershed event in all the life sciences, especially paleontology. Fossils had played a role in the development of Darwin's theory. In particular he had been impressed by fossils he had collected in South America during the voyage of the Beagle of giant armadillos, giant sloths, and what at the time he thought were giant llamas that seemed to be related to species still living on the continent in modern times. The scientific debate that started immediately after the publication of *Origin* led to a concerted effort to look for transitional fossils and other evidence of evolution in the fossil record. There were two areas where early success attracted considerable public attention, the transition between reptiles and birds, and the evolution of the modern single-toed horse. In 1861 the first specimen of *Archaeopteryx*, an animal with both teeth and feathers and a mix of other reptilian and avian features, was discovered in a limestone quarry in Bavaria and described by Richard Owen. Another would be found in the late 1870s and put on display at the Natural History Museum, Berlin in 1881. Other primitive toothed birds were found by Othniel Marsh in Kansas in 1872. Marsh also discovered fossils of several primitive horses in the Western United States that helped trace the evolution of the horse from the small 5-toed *Hyracotherium* of the Eocene to the much larger single-toed modern horses of the genus *Equus*. Thomas Huxley would make extensive use of both the horse and bird fossils in his advocacy of evolution. Acceptance of evolution occurred rapidly in scientific circles, but acceptance of Darwin's proposed mechanism of natural selection as the driving force behind it was much less universal. In particular some paleontologists such as Edward Drinker Cope and Henry Fairfield Osborn preferred alternatives such as neo-Lamarckism, the inheritance of characteristics acquired during life, and orthogenesis, an innate drive to change in a particular direction, to explain what they perceived as linear trends in evolution.

There was also great interest in human evolution. Neanderthal fossils were discovered in 1856, but at the time it was not clear that they represented a different species from modern humans. Eugene Dubois created a sensation with his discovery of Java Man, the first fossil evidence of a species that seemed clearly intermediate between humans and apes, in 1891.

Developments in North America

A major development in the second half of the 19th century was a rapid expansion of paleontology in North America. In 1858 Joseph Leidy described a *Hadrosaurus* skeleton, which was the first North American dinosaur to be described from good remains. However, it was the massive westward expansion of railroads, military bases, and settlements into Kansas and other parts of the Western United States following the American Civil War that really fueled the expansion of fossil collection. The result was an increased understanding of the natural history of North America, including the discovery of the Western Interior Sea that had covered Kansas and much of the rest of the Midwestern United States during parts of the Cretaceous, the discovery of several important fossils of primitive birds and horses, and the discovery of a number of new dinosaur genera including *Allosaurus*, *Stegosaurus*, and *Triceratops*. Much of this activity was part of a fierce personal and professional rivalry between two men, Othniel Marsh, and Edward Cope, which has become known as the Bone Wars.

Overview of developments in the 20th century

Developments in geology

Two 20th-century developments in geology had a big effect on paleontology. The first was the development of radiometric dating, which allowed absolute dates to be assigned to the geologic timescale. The second was the theory of plate tectonics, which helped make sense of the geographical distribution of ancient life.

Geographical expansion of paleontology

During the 20th century, paleontological exploration intensified everywhere and ceased to be a largely European and North American activity. In the 135 years between Buckland's first discovery and 1969 a total of 170 dinosaur genera were described. In the 25 years after 1969 that number increased to 315. Much of this increase was due to the examination of new rock exposures, particularly in previously little-explored areas in South America and Africa. Near the end of the 20th century the opening of China to systematic exploration for fossils has yielded a wealth of material on dinosaurs and the origin of birds and mammals. Also study of the Chengjiang fauna, a Cambrian fossil site in China, during the 1990s has provided important clues to the origin of vertebrates.

Mass extinctions

The 20th century saw a major renewal of interest in mass extinction events and their effect on the course of the history of life. This was particularly true after 1980 when Luis and Walter Alvarez put forward the Alvarez hypothesis claiming that an impact event caused the Cretaceous–Paleogene extinction event, which killed off the non-avian dinosaurs along with many other living things. Also in the early 1980s Jack Sepkoski and David M. Raup published papers with statistical analysis of the fossil record of marine invertebrates that revealed a pattern (possibly cyclical) of repeated mass extinctions with significant implications for the evolutionary history of life.

Evolutionary paths and theory

Throughout the 20th century new fossil finds continued to contribute to understanding the paths taken by evolution. Examples include major taxonomic transitions such as finds in Greenland, starting in the 1930s (with more major finds in the 1980s), of fossils illustrating the evolution of tetrapods from fish, and fossils in China during the 1990s that shed light on the dinosaur-bird relationship. Other events that have attracted considerable attention have included the discovery of a series of fossils in Pakistan that have shed light on whale evolution, and most famously of all a series of finds throughout the 20th century in Africa (starting with Taung child in 1924) and elsewhere have helped illuminate the course of human evolution. Increasingly, at the end of the 20th century, the results of paleontology and molecular biology were being brought together to reveal detailed phylogenetic trees.

The results of paleontology have also contributed to the development of evolutionary theory. In 1944 George Gaylord Simpson published *Tempo and Mode in Evolution*, which used quantitative analysis to show that the fossil record was consistent with the branching, non-directional, patterns predicted by the advocates of evolution driven by natural selection and genetic drift rather than the linear trends predicted by earlier advocates of neo-Lamarckism and orthogenesis. This integrated paleontology into the modern evolutionary synthesis. In 1972 Niles Eldredge and Stephen Jay Gould used fossil evidence to advocate the theory of punctuated equilibrium, which maintains that evolution is characterized by long periods of relative stasis and much shorter periods of relatively rapid change.

Cambrian explosion

One area of paleontology that has seen a lot of activity during the 1980s, 1990s, and beyond is the study of the Cambrian explosion during which many of the various phyla of animals with their distinctive body plans first appear. The well-known Burgess Shale Cambrian fossil site was found in 1909 by Charles Doolittle Walcott, and another important site in Chengjiang China was found in 1912. However, new analysis in the 1980s by Harry B. Whittington, Derek Briggs, Simon Conway Morris and others sparked a renewed interest and a burst of activity including discovery of an important new fossil site, Sirius Passet, in Greenland, and the publication of a popular and controversial book, *Wonderful Life* by Stephen Jay Gould in 1989.

Pre-Cambrian fossils

Prior to 1950 there was no widely accepted fossil evidence of life before the Cambrian period. When Charles Darwin wrote *The Origin of Species* he acknowledged that the lack of any fossil evidence of life prior to the relatively complex animals of the Cambrian was a potential argument against the theory of evolution, but expressed the hope that such fossils would be found in the future. In the 1860s there were claims of the discovery of pre-Cambrian fossils, but these would later be shown not to have an organic origin. In the late 19th century Charles Doolittle Walcott would discover stromatolites and other fossil evidence of pre-Cambrian life, but at the time the organic origin of those fossils was also disputed. This would start to change in the 1950s with the discovery of more stromatolites along with microfossils of the bacteria that built them, and the publication of a series of papers by the Soviet scientist Boris Vasil'evich Timofeev announcing the discovery of microscopic fossil spores in pre-Cambrian sediments. A key breakthrough would come when Martin Glaessner would show that fossils of soft bodied animals discovered by Reginald Sprigg during the late 1940s in the Ediacaran hills of Australia were in fact pre-Cambrian not early Cambrian as Sprigg had originally believed, making the Ediacaran biota the oldest animals known. By the end of the 20th century, paleobiology had established that the history of life extended back at least 3.5 billion years.

Chapter 37

Stubs

History of industrial ecology

The establishment of industrial ecology as field of scientific research is commonly attributed to an article devoted to industrial ecosystems, written by Frosch and Gallopoulos, which appeared in a 1989 special issue of Scientific American. Industrial ecology emerged from several earlier ideas and concepts, some of which date back to the 19th century.

Before the 1960s

The term "industrial ecology" has been used alongside "industrial symbiosis" at least since the 1940s. Economic geography was perhaps one of the first fields to use these terms. For example, in an article published in 1947, George T. Renner refers to "The General Principle of Industrial Location" as a "Law of Industrial Ecology". Briefly stated this is:

Any industry tends to locate at a point which provides optimum access to its ingredients or component elements. If all these component elements be juxtaposed, the location of the industry is predetermined. If, however, they occur widely separated, the industry is so located as to be most accessible to that element which would be the most expensive or difficult to transport and which, therefore, becomes the locative factor for the industry in question.

In the same article the author defines and describes industrial symbiosis:

Often the location of an industry cannot be fully understood solely in terms of its locative ingredient elements. There are relationships between industries, sometimes simple, but often quite complex, which enter into and complicate the analysis. Chief among these is the phenomenon of industrial symbiosis. By this is meant the consorting together of two or more of dissimilar industries. Industrial Symbiosis, when scrutinized, is seen to be of two kinds, disjunctive and conjunctive.

It appears that the concept of Industrial Symbiosis was not new for the field of economic geography, since the same categorization is used by Walter G. Lezius in his 1937 article "Geography of Glass Manufacture at Toledo, Ohio", also published in the Journal of Economic Geography.

Used in a different context, the term "Industrial Ecology" is also found in a 1958 paper concerned with the relationship between the ecological impact from increasing urbanization and value orientations of related peoples. The case study is in Lebanon:

The central ecological variable in the present research is ecological mobility, or the movement of men in space. It is patent that modern Industrial Ecology requires more such adaptive mobility than does traditional folk-village organization.

1960s

In 1963, we find the term Industrial Ecology (defined as the "complex ecology of the modern industrial world") being used to describe the social nature and complexity of (and within) industrial systems:

...industrial organisations are social rather than mechanical systems. A firm is not only a working organisation with a working purpose. It is rather a community with its own 'politics', in so far as it is involved in problems concerned with the proper distribution of power between individuals and groups of individuals and with questions of individual and group prestige, influence, status and standing... [and he concludes that] the understanding which the student of management is expected to gain is no less than the attainment of insight into an Industrial Ecology of great complexity.

In 1967, the President of the American association for the advancement of science writes in "The experimental city" that "There are examples of industrial symbiosis where one industry feeds off, or at least neutralizes, the wastes of another..." The same author in 1970 talks about "The Next Industrial Revolution" The concept of material and energy sharing and reuse is central to his proposal for a new industrial revolution and he cites agro-industrial symbiosis as a practical way for achieving this:

The object of the next industrial revolution is to ensure that there will be no such thing as waste, on the basis that waste is simply some substance that we do not vet have the wit to use...

The next industrial revolution is this generating of a huge new [industry that]... will not produce products, it will rather reprocess the things we call wastes so they may be reproduced in the factories into the things we need... Having the city near the rural area will enable waste heat to be used to speed up the biological processes of treating the organic wastes before they go back into the land. This might end in an elegant arrangement-the power plants located close enough to the center of use, to the people who need the power, but also, within the economics, close enough to the agriculture lands so that the waste heat may be used there. This is an example of agro-industrial symbiosis, if you like to call it that.

In these early articles, "Industrial Ecology" is used in its literal sense - as a system of interacting industrial entities. The relation to natural ecosystems (through either metaphor or analogy) is not explicit. Industrial Symbiosis on the other hand, is already clearly defined as a type of industrial organization, and the term symbiosis is borrowed from the ecological sciences to describe an analogous phenomenon in industrial systems.

1970s

Industrial Ecology has been a research subject of the Japan Industrial Policy Research Institute since 1971. Their definition of Industrial Ecology is "research for the prospect of dynamic harmonization between human activities and nature by a systems approach based upon ecology (JIPRI, 1983)". This programme has resulted to a number of reports that are available only in Japanese.

One of the earliest definitions of Industrial Ecology was proposed by Harry Zvi Evan at a seminar of the Economic Commission of Europe in Warsaw (Poland) in 1973 (an article was subsequently published by Evan in the Journal for International Labour Review in 1974 vol. 110 (3), pp. 219–233). Evan defined Industrial Ecology as a systematic analysis of industrial operations including factors like: Technology, environment, natural resources, bio-medical aspects, institutional and legal matters as well as the socio-economic aspects.

In 1974 the term of Industrial Ecology is perhaps for the first time associated with a cyclical production mode (rather than a linear one, resulting to waste). In this article, the necessity for a transition to an "open-world Industrial Ecology", is used as argument for the need to establish lunar industries:

Low living standards provide one strong motive for most developing countries to increase their productivity and grow economically. Population increase (while it lasts) is a still more powerful driver for increased world consumption. Thus the pressure on resources will continue to grow. Instead of deploring it, we better grow with it. Only through transition to an open-world Industrial Ecology - which includes both benign industrial revolution on Earth and extraterrestrial industrialization - can the present apparent limits to growth be overcome.

Many elements of modern Industrial Ecology were commonplace in the industrial sectors of the former Soviet Union. For example, “kombinirovanaia produksia” (combined production) was present from the earliest years of the Soviet

Union and was instrumental in shaping the patterns of Soviet industrialization. “Bezotkhodnoyi tekhnologii” (waste-free technology) was introduced in the final decades of the USSR as a way to increase industrial production while limiting environmental impact. Fiodor Davitaya, a Soviet scientist from the Republic of Georgia, described in 1977 the analogy relating industrial systems to natural systems as a model for a desirable transition to cleaner production:

Nature operates without any waste products. What is rejected by some organisms provides food for others. The organisation of industry on this principle—with the waste products of some branches of industry providing raw material for others—means in effect using natural processes as a model, for in them the resolution of all arising contradictions is the motive force of progress.

1980s

By the 80s Industrial Ecology was already "promoted" to a research subject, which several institutes around the globe embraced. In a 1986 article published in *Ecological Modelling*, there is a full description of Industrial Ecology and the analogy to natural ecosystems is clearly stated:

The structure and inner-working of an industrial society resemble those of a natural ecosystem. The concepts in ecology such as habitat, succession, trophic level, limiting factors and community metabolism can also apply to the study of the ecology of an industrial society. For instance, an industry in a society may grow or decline as a consequence of dynamic changes in exogenous limiting resources and in the hierarchical and/or metabolic structure of that society. When studying the ecology of an industrial society (henceforth termed 'Industrial Ecology'), these concepts and methodologies employed in ecosystems analyses are useful.

In fact, in the above article there is an attempt to model an "industrial ecological system". The model is composed of seven major sections: industry, population, labor force, living state, environment and pollution, general health, and occupational health. Notice the rough similarity with Evan's factors as stated in the above section.

During the 80s the emergence of another related term, "industrial metabolism", is observed. The term is used as a metaphor for the organization and functioning of industrial activity. In an article defending the "biological modulation of terrestrial carbon cycle", the author includes an extraordinary parenthetical note:

it is an intrinsic property of life to proliferate exponentially until the encounter of limits set by (I) the availability of biologically utilizable reducing power, or (2) the exhaustion of some critical nutrient, or (3) an autotoxic effect imposed by life on its own environment. These limits are universal, applying to microbial ecosystems as well as to the population dynamics of a seemingly unrestricted biological superdominant such as Homo Sapiens (here, the ultimate limit is likely to be placed by an autotoxic effect exerted by the "extrasomatic" (industrial) metabolism of the human race).

1989 – Decisive articles

In 1989 two articles were released that played a decisive role in the history of industrial ecology. The first one was titled "Industrial Metabolism" by Robert Ayres. Ayres essentially lays the foundations of Industrial Ecology, although the term is not to be found in this article. In the appendix of the article he includes "a theoretical exploration of the biosphere and the industrial economy as material-transformation systems and lessons that might be learned from their comparison". He proposes that:

We may think of both the biosphere and the industrial economy as systems for the transformation of materials. The biosphere as it now exists is nearly a perfect system for recycling materials. This was not the case when life on earth began. The industrial system of today resembles the earliest stage of biological evolution, when the most primitive living organisms obtained their energy from a stock of organic molecules accumulated during prebiotic times. It is increasingly urgent for us to learn from the biosphere and modify our industrial metabolism, the energy - and value - yielding process essential to economic development... we should not only postulate, but indeed endorse, a long-run imperative favoring an industrial metabolism that results in reduced extraction of virgin materials, reduced loss of waste materials, and increased recycling of useful ones.

The term "Industrial Ecology" gains mainstream attention later the same year (1989) through a "Scientific American" article named "Strategies for Manufacturing". In this article, R.Frosch and N.Gallopoulos wonder "why would not our industrial system behave like an ecosystem, where the wastes of a species may be resource to another species? Why would not the outputs of an industry be the inputs of another, thus reducing use of raw materials, pollution, and saving on waste treatment?"

This vision gave birth to the concept of the Eco-industrial Park, the industrial complex that is governed by Industrial Ecology principles. A notable example resides in a Danish industrial park in the city of Kalundborg. There, several linkages of byproducts and waste heat can be found between numerous entities such as a large power plant, an oil refinery, a pharmaceutical plant, a plasterboard factory, an enzyme manufacturer, a waste company and the city itself.

Frosch's and Gallopoulos' thinking was in certain ways simply an extension of earlier ideas, such as the efficiency and waste-reduction thinking annunciated by Buckminster Fuller and his students (e.g., J. Baldwin), and parallel ideas about energy cogeneration, such as those of Amory Lovins and the Rocky Mountain Institute.

21st century

The *Journal of Industrial Ecology* (since 1997), the International Society for Industrial Ecology (since 2001), and the journal *Progress in Industrial Ecology* (since 2004) have covered industrial ecology in the international scientific community. Principles of industrial ecology are also emerging in various policy realms such as the concept of the circular economy that is being promoted in China. Although the definition of the circular economy has yet to be formalized, generally the focus is on strategies such as creating a circular flow of materials, and cascading energy flows. An example of this would be using waste heat from one process to run another process that requires a lower temperature. This maximizes the efficiency of exergy use. This strategy aims for a more efficient economy with fewer pollutants and other unwanted by-products.

History of fluorine

Fluorine is a relatively new element in human applications. In ancient times, only minor uses of fluorine-containing minerals existed. The industrial use of fluorite, fluorine's source mineral, was first described by early scientist Georgius Agricola in the 16th century, in the context of smelting. The name "fluorite" (and later "fluorine") derives from Agricola's invented Latin terminology. In the late 18th century, hydrofluoric acid was discovered. By the early 19th century, it was recognized that fluorine was a bound element within compounds, similar to chlorine. Fluorite was determined to be calcium fluoride.

Because of fluorine's tight bonding as well as the toxicity of hydrogen fluoride, the element resisted many attempts to isolate it. In 1886, French chemist Henri Moissan, later a Nobel Prize winner, succeeded in making elemental fluorine by electrolyzing a mixture of potassium fluoride and hydrogen fluoride. Large-scale production and use of fluorine began during World War 2 as part of the Manhattan Project. Earlier in the century, the main fluorochemicals were commercialized by the DuPont company: refrigerant gases (Freon) and polytetrafluoroethylene plastic (Teflon).

Ancient use

Some instances of ancient use of fluorite, main source mineral of fluorine, for ornamental use carvings exist. However, archeological finds are rare, perhaps in part because of the stone's softness. Two Roman cups made of Persian fluorite have been discovered and are currently exhibited at the British museum. Pliny the Elder described a soft stone from Persia used in cups that may have been fluorite.

Fluorite carvings from about 1000 AD have been discovered in the Americas in Indian burial grounds.

Early metallurgy

The word "fluorine" derives from the Latin stem of the main source mineral, fluorite, which was first mentioned in 1529 by Georgius Agricola, the "father of mineralogy". He described fluorite as a flux—an additive that helps melt ores and slags during smelting. Fluorite stones were called *schone flusse* in the German of the time. Agricola, writing in Latin but describing 16th century industry, invented several hundred new Latin terms. For the *schone flusse* stones, he used the Latin noun *fluores*, "fluxes", because they made metal ores flow when in a fire. After Agricola, the name for the mineral evolved to fluorspar (still commonly used) and then to fluorite.

Fluorite mineral was also described in the writings of alchemist Basilius Valentinus, supposedly in the late 15th century. However, it is alleged that "Valentinus" was a hoax as his writings were not known until about 1600.

Hydrofluoric acid

Some sources claim that the first production of hydrofluoric acid was by Heinrich Schwanhard, a German glass cutter, in 1670. A peer-reviewed study of Schwanhard's writings, though, showed no specific mention of fluorite and only discussion of an extremely strong acid. It was hypothesized that this was probably nitric acid or aqua regia, both capable of etching soft glass.

Andreas Sigismund Marggraf made the first definite preparation of hydrofluoric acid in 1764 when he heated fluorite with sulfuric acid in glass, which was greatly corroded by the product. In 1771, Swedish chemist Carl Wilhelm Scheele repeated this reaction. Scheele recognized the product of the reaction as an acid, which he called "fluss-spats-syran" (fluor-spar-acid); in English, it was known as "fluoric acid".

Recognition of the element

In 1810, French physicist André-Marie Ampère suggested that hydrofluoric acid was a compound of hydrogen with an unknown element, analogous to chlorine. Fluorite was then shown to be mostly composed of calcium fluoride.

Sir Humphry Davy originally suggested the name *fluorine*, taking the root from the name of "fluoric acid" and the -ine suffix, similarly to other halogens. This name, with modifications, came to most European languages. (Greek, Russian, and several other languages use the name *ftor* or derivatives, which was suggested by Ampère and comes from the Greek φθόριος (*phthorios*), meaning "destructive".) The New Latin name (*fluorum*) gave the element its current symbol, F, although the symbol Fl has been used in early papers. The symbol Fl is now used for the super-heavy element flerovium.

Early isolation attempts

Progress in isolating the element was slowed by the exceptional dangers of generating fluorine: several 19th century experimenters, the "fluorine martyrs", were killed or blinded. Humphry Davy, as well as the notable French chemists Joseph Louis Gay-Lussac and Louis Jacques Thénard, experienced severe pains from inhaling hydrogen fluoride gas; Davy's eyes were damaged. Irish chemists Thomas and George Knox developed fluorite apparatus for working with hydrogen fluoride, but nonetheless were severely poisoned. Thomas nearly died and George was disabled for three years. French chemist Henri Moissan was poisoned several times, which shortened his life. Belgian chemist Paulin Louyet and French chemist Jérôme Nicklès [de] tried to follow the Knox work, but they died from HF poisoning even though they were aware of the dangers.

Initial attempts to isolate the element were also hindered by material difficulties: the extreme corrosiveness and reactivity of hydrogen fluoride (and of fluorine gas) as well as problems getting a suitable conducting liquid for electrolysis. Davy tried to electrolyze HF but had to stop because the electrodes were damaged. He then shifted to (unsuccessful) chemical reactions.

Edmond Frémy thought that passing electric current through pure hydrofluoric acid (dry HF) might work. Previously, hydrogen fluoride was only available in a water solution. Frémy therefore devised a method for producing dry hydrogen fluoride by acidifying potassium bifluoride (KHF_2). Unfortunately, pure hydrogen fluoride did not pass an electric current. Frémy also tried electrolyzing molten calcium fluoride and probably produced some fluorine (since he made calcium metal at the other electrode), but he was unable to collect the gas.

English chemist George Gore also tried electrolyzing dry HF and may have made small quantities of fluorine gas in 1860. He reported an explosion after running his cell (hydrogen and fluorine recombine dramatically), but he recognized that an oxygen leak could have also caused the reaction.

Moissan

French chemist Henri Moissan, formerly one of Frémy's students, continued the search. After trying many different approaches, he built on Frémy and Gore's earlier attempts by combining potassium bifluoride and hydrogen fluoride. The resultant solution conducted electricity. Moissan also constructed especially corrosion-resistant equipment: containers crafted from a mixture of platinum and iridium (more chemically resistant than pure platinum) with fluorite stoppers. After 74 years of effort by many chemists, on 26 June 1886, Moissan isolated elemental fluorine. Moissan's report to the French Academy of making fluorine showed appreciation for the feat: "One can indeed make various hypotheses on the nature of the liberated gas; the simplest would be that *we are in the presence of fluorine*."

Moissan's 1887 publication documents reaction attempts of fluorine gas with several substances: sulfur (flames), hydrogen (explosion), carbon (no reaction), etc. Later, Moissan devised a less expensive apparatus for making fluorine: copper equipment coated with copper fluoride. Moissan also constructed special apparatus—5m long platinum tubes with fluorite windows—to determine the slight yellow color of fluorine gas. (The gas appears transparent in small tubes or when allowed to escape. The color observation was not repeated until the 1980s, when his result was confirmed.)

In 1906, two months before his death, Moissan received the Nobel Prize in chemistry. The citation:

...in recognition of the great services rendered by him in his investigation and isolation of the element fluorine...The whole world has admired the great experimental skill with which you have studied that savage beast among the elements.

Development

During the 1930s and 1940s, the DuPont company commercialized organofluorine compounds at large scales. Following trials of chlorofluorcarbons as refrigerants by researchers at General Motors, DuPont developed large-scale production of Freon-12. The work was carried out by DuPont scientist Dr. Tomas Midgley Jr. DuPont and GM formed a joint venture in 1930 to market the new product; in 1949 DuPont took over the business. Freon proved to be a marketplace hit, rapidly replacing earlier, more toxic, refrigerants and growing the overall market for kitchen refrigerators.

In 1938, polytetrafluoroethylene (Teflon) was discovered by accident by a recently hired DuPont PhD, Roy J. Plunkett. While working with a cylinder of tetrafluoroethylene, he was unable to release the gas, although the weight had not changed. Scraping down the container, he found white flakes of a polymer new to the world. Tests showed the substance was resistant to corrosion from most substances and had better high temperature stability than any other plastic. By early 1941, a crash program was making commercial quantities.

Large-scale productions of elemental fluorine began during World War II. Germany used high-temperature electrolysis to produce tons of chlorine trifluoride, a compound planned to be used as an incendiary. The Manhattan project in the United States produced even more fluorine for use in uranium separation. Gaseous uranium hexafluoride was used to separate uranium-235, an important nuclear explosive, from the heavier uranium-238 in diffusion plants. Because uranium hexafluoride releases small quantities of corrosive fluorine, the separation plants were built with special materials. All pipes were coated with nickel; joints and flexible parts were fabricated from Teflon.

In 1958, a DuPont research manager in the Teflon business, Bill Gore, left the company because of its unwillingness to develop Teflon as wire-coating insulation. Gore's son Robert found a method for solving the wire-coating problem and the company W. L. Gore and Associates was born. In 1969, Robert Gore developed an expanded polytetrafluoroethylene (ePTFE) membrane which led to the large Gore-Tex business in breathable rainwear. The company developed many other uses of PTFE.

In the 1970s and 1980s, concerns developed over the role chlorofluorocarbons play in damaging the ozone layer. By 1996, almost all nations had banned chlorofluorocarbon refrigerants and commercial production ceased. Fluorine continued to play a role in refrigeration though: hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) were developed as replacement refrigerants.

History of the metric system

The history of the metric system began during the Age of Enlightenment with measures of length and weight derived from nature, along with their decimal multiples and fractions. The system became the standard of France and Europe within half a century. Other measures with unity ratios were added, and the system went on to be adopted across the world.

The first practical realisation of the metric system came in 1799, during the French Revolution, after the existing system of measures had become impractical for trade, and was replaced by a decimal system based on the kilogram and the metre. The basic units were taken from the natural world. The unit of length, the metre, was based on the dimensions of the

Earth, and the unit of mass, the kilogram, was based on the mass of a volume of water of one litre (a cubic decimetre). Reference copies for both units were manufactured in platinum and remained the standards of measure for the next 90 years. After a period of reversion to the *mesures usuelles* due to unpopularity of the metric system, the metrication of France and much of Europe was complete by the 1850s.

In the middle of the 19th century, James Clerk Maxwell conceived a coherent system where a small number of units of measure were defined as base units, and all other units of measure, called derived units, were defined in terms of the base units. Maxwell proposed three base units for length, mass and time. Advances in electromagnetism in the 19th century necessitated additional units to be defined, and multiple incompatible systems of such units came into use; none could be reconciled with the existing dimensional system. The impasse was resolved by Giovanni Giorgi, who in 1901 proved that a coherent system that incorporated electromagnetic units required a fourth base unit, of electromagnetism.

The seminal 1875 Treaty of the Metre resulted in the fashioning and distribution of metre and kilogram artefacts, the standards of the future coherent system that became the SI, and the creation of an international body *Conférence générale des poids et mesures* or CGPM to oversee systems of weights and measures based on them.

In 1960, the CGPM launched the International System of Units (in French the *Système international d'unités* or SI) with six "base units": the metre, kilogram, second, ampere, degree Kelvin (subsequently renamed the "kelvin") and candela, plus

16 more units derived from the base units. A seventh base unit, the mole, and six other derived units were added later in the 20th century. During this period, the metre was redefined in terms of the speed of light, and the second was redefined based on the microwave frequency of a caesium atomic clock.

Due to the instability of the international prototype of the kilogram, a series of initiatives were undertaken, starting in the late 20th century, to redefine the ampere, kilogram, mole and kelvin in terms of invariant constants of physics, ultimately resulting in the 2019 redefinition of the SI base units, which finally eliminated the need for any physical reference artefacts - notably, this enabled the retirement of the standard kilogram.

Age of Enlightenment

Foundational aspects of mathematics and culture, together with advances in the sciences during the Enlightenment, set the stage for the emergence in the late 18th century of a system of measurement with rationally related units and simple rules for combining them.

Preamble

In the early ninth century, when much of what later became France was part of the Holy Roman Empire, units of measure had been standardised by the Emperor Charlemagne. He had introduced standard units of measure for length and for mass throughout his empire. As the empire disintegrated into separate nations, including France, these standards diverged.

In England the Magna Carta (1215) had stipulated that "There shall be standard measures of wine, ale, and corn (the London quarter), throughout the kingdom. There shall also be a standard width of dyed cloth, russet, and haberject, namely two ells within the selvedges. Weights are to be standardised similarly."

During the early medieval era, Roman numerals were used in Europe to represent numbers, but the Arabs represented numbers using the Hindu numeral system, a positional notation that used ten symbols. In about 1202, Fibonacci published his book *Liber Abaci* (Book of Calculation) which introduced the concept of positional notation into Europe. These symbols evolved into the numerals "0", "1", "2" etc. At that time there was dispute regarding the difference between rational numbers and irrational numbers and there was no consistency in the way in which decimal fractions were represented.

Simon Stevin is credited with introducing the decimal system into general use in Europe. In 1586, he published a small pamphlet called *De Thiende* ("the tenth") which historians credit as being the basis of modern notation for decimal fractions. Stevin felt that this innovation was so significant that he declared the universal introduction of decimal coinage, measures, and weights to be merely a question of time.

Body measures and artefacts

Since the time of Charlemagne, the standard of length had been a measure of the body, that from fingertip to fingertip of the outstretched arms of a large man, from a family of body measures called *fathoms*, originally used among other things, to measure depth of water. An artefact to represent the standard was cast in the most durable substance available in the Middle Ages, an iron bar. The problems of a non-reproducible artefact became apparent over the ages: it rusted, was stolen, beaten into a mortised wall until it bent, and was at times lost. When a new royal standard had to be cast, it was a different standard than the old one, so replicas of old ones and new ones came into existence and use. The artefact existed through the 18th century, and was called a *teise* or later, a *toise* (from Latin *tense*: outstretched (arms)). This would lead to a search in the 18th century for a reproducible standard based on some invariant measure of the natural world.

Clocks and pendulums

In 1656, Dutch scientist Christiaan Huygens invented the pendulum clock, with its pendulum marking the seconds. This gave rise to proposals to use its length as a standard unit. But it became apparent that the pendulum lengths of calibrated clocks in different locations varied (due to local variations in the acceleration due to gravity), and this was not a good solution. A more uniform standard was needed.

In 1670, Gabriel Mouton, a French abbot and astronomer, published the book *Observationes diametrorum solis et lunae apparentium* ("Observations of the apparent diameters of the Sun and Moon") in which he proposed a decimal system of measurement of length for use by scientists in international communication, to be based on the dimensions of the Earth. The *milliare* would be defined as a minute of arc along a meridian and would be divided into 10 centuria, the centuria into 10 decuria and so on, successive units being the virga, virgula, decima, centesima, and the millesima. Mouton used Riccioli's estimate that one degree of arc was 321,185 Bolognese feet, and his own experiments showed that a pendulum of length one virgula would beat 3959.2 times in half an hour. He believed that with this information scientists in a foreign country would be able to construct a copy of the virgula for their own use. Mouton's ideas attracted interest at the time; Picard in his work *Mesure de la Terre* (1671) and Huygens in his work *Horologium Oscillatorium sive de motu pendulorum* ("Of oscillating clocks, or concerning the motion of pendulums", 1673) both proposing that a standard unit of length be tied to the beat frequency of a pendulum.

The shape and size of the Earth

Since at least the Middle Ages, the Earth had been perceived as eternal, unchanging and of symmetrical shape (close to a sphere), so it was natural that some fractional measure of its surface should be proposed as a standard of length. But first, scientific information about the shape and size of the Earth had to be obtained.

In 1669, Jean Picard, a French astronomer, was the first person to measure the Earth accurately. In a survey spanning one degree of latitude, he erred by only 0.44%.

In *Philosophiæ Naturalis Principia Mathematica* (1686), Isaac Newton gave a theoretical explanation for the "bulging equator" which also explained the differences found in the lengths of the "second pendulums", theories that were confirmed by the

French Geodesic Mission to Peru undertaken by the French Academy of Sciences in 1735.

Late 18th century: conflict and lassitude

By the mid-18th century, it had become apparent that it was necessary to standardise of weights and measures between nations who traded and exchanged scientific ideas with each other. Spain, for example, had aligned her units of measure with the royal units of France. and Peter the Great aligned the Russian units of measure with those of England. In 1783 the British inventor James Watt, who was having difficulties in communicating with German scientists, called for the creation of a global decimal measurement system, proposing a system which used the density of water to link length and mass, and in 1788 the French chemist Antoine Lavoisier commissioned a set of nine brass cylinders (a [French] pound and decimal subdivisions thereof) for his experimental work.

In 1790, a proposal floated by the French to Britain and the United States, to establish a uniform measure of length, a *metre* based on the period of a pendulum with a beat of one second, was defeated in the British Parliament and United States Congress. The underlying issue was failure to agree on the latitude for the definition, since gravitational acceleration, and therefore the length of the pendulum, varies (inter alia) with latitude: each party wanted a definition according to a major latitude passing through their own country. The direct consequences of the failure were the French unilateral development and deployment of the metric system and its spread by trade to the continent; the British adoption of the Imperial System of Measures throughout the realm in 1824;

and the United States' retention of the British common system of measures in place at the time of the independence of the colonies. This was the position that continued for nearly the next 200 years.

Implementation in Revolutionary France

Weights and measures of the *Ancien Régime*

It has been estimated that on the eve of the Revolution in 1789, the eight hundred or so units of measure in use in France had up to a quarter of a million different definitions because the quantity associated with each unit could differ from town to town, and even from trade to trade. Although certain standards, such as the *pied du roi* (the King's foot) had a degree of pre-eminence and were used by scientists, many traders chose to use their own measuring devices, giving scope for fraud and hindering commerce and industry. These variations were promoted by local vested interests, but hindered trade and taxation.

The units of weight and length

In 1790, a panel of five leading French scientists was appointed by the *Académie des sciences* to investigate weights and measures. They were Jean-Charles de Borda, Joseph-Louis

Lagrange, Pierre-Simon Laplace, Gaspard Monge and Nicolas de Condorcet. Over the following year, the panel, after studying various alternatives, made a series of recommendations regarding a new system of weights and measures, including that it should have a decimal radix, that the unit of length should be based on a fractional arc of a quadrant of the Earth's meridian, and that the unit of weight should be that of a cube of water whose dimension was a decimal fraction of the unit of length. The proposals were accepted by the French Assembly on 30 March 1791.

Following acceptance, the *Académie des sciences* was instructed to implement the proposals. The *Académie* broke the tasks into five operations, allocating each part to a separate working group:

- Measuring the difference in latitude between Dunkirk and Barcelona and triangulating between them
- Measuring the baselines used for the survey
- Verifying the length of the second pendulum at 45° latitude.
- Verifying the weight in a vacuum of a given volume of distilled water.
- Publishing conversion tables relating the new units of measure to the existing units of measure.

The panel decided that the new measure of length should be equal to one ten-millionth of the distance from the North Pole to the Equator (the quadrant of the Earth's circumference), measured along the meridian passing through Paris.

Using Jean Picard's survey of 1670 and Jacques Cassini's survey of 1718, a provisional value of 443.44 *lignes* was assigned to the metre which, in turn, defined the other units of measure.

While Méchain and Delambre were completing their survey, the commission had ordered a series of platinum bars to be made based on the provisional metre. When the final result was known, the bar whose length was closest to the meridional definition of the metre would be selected.

After 1792 the name of the original defined unit of mass, "*gramme*", which was too small to serve as a practical realisation for many purposes, was adopted, the new prefix "kilo" was added to it to form the name "*kilogramme*". Consequently, the kilogram is the only SI base unit that has an SI prefix as part of its unit name. A provisional kilogram standard was made and work was commissioned to determine the precise mass of a cubic decimetre (later to be defined as equal to one litre) of water. The regulation of trade and commerce required a "practical realisation": a single-piece, metallic reference standard that was one thousand times more massive that would be known as the *grave*. This mass unit defined by Lavoisier and René Just Haüy had been in use since 1793. This new, practical realisation would ultimately become the base unit of mass. On 7 April 1795, the *gramme*, upon which the kilogram is based, was decreed to be equal to "the absolute weight of a volume of pure water equal to a cube of one hundredth of a metre, and at the temperature of the melting ice". Although the definition of the *kilogramme* specified water at 0 °C – a highly stable temperature point – it was replaced with the temperature at which water reaches maximum density. This temperature, about 4 °C, was not accurately known, but one of the advantages of the new definition was that the precise Celsius value of the temperature was not actually important. The final conclusion was that one cubic decimetre of water at its maximum density was equal to 99.92072% of the mass of the provisional kilogram.

On 7 April 1795 the metric system was formally defined in French law. It defined six new decimal units:

- The *mètre*, for length – defined as one ten-millionth of the distance between the North Pole and the Equator through Paris
- The *are* (100 m) for area [of land]
- The *stère* (1 m) for volume of firewood
- The *litre* (1 dm) for volumes of liquid
- The *gramme*, for mass – defined as the mass of one cubic centimetre of water
- The *franc, for currency.*
- *Historical note: only the metre and (kilo)gramme defined here went on to become part of later metric systems.*

Decimal multiples of these units were defined by Greek prefixes: *"myria-"* (10,000), *"kilo-"* (1000), *"hecto-"* (100) and *"deka-"* (10) and submultiples were defined by the Latin prefixes *"deci-"* (0.1), *"centi-"* (0.01) and *"milli-"* (0.001).

The 1795 draft definitions enabled provisional copies of the kilograms and metres to be constructed.

Meridional survey

- The task of surveying the meridian arc, which was estimated to take two years, fell to Pierre Méchain and Jean-Baptiste Delambre. The task eventually took more than six years (1792–1798) with delays caused not only by unforeseen technical difficulties but also by the convulsed period of the aftermath of the Revolution. Apart from the obvious nationalistic considerations, the Paris meridian was also a sound choice for practical scientific reasons: a portion of the quadrant from Dunkirk to Barcelona (about 1000 km, or one-tenth of the total) could be surveyed with start- and end-points at sea level, and that portion was roughly in the middle of the quadrant, where the effects of the Earth's oblateness were expected to be the largest.The project was split into two parts – the northern section of 742.7 km from the Belfry, Dunkirk to Rodez Cathedral which was surveyed by Delambre and the southern section of 333.0 km from Rodez to the Montjuïc Fortress, Barcelona which was surveyed by Méchain.

Delambre used a baseline of about 10 km in length along a straight road, located close to Melun. In an operation taking six weeks, the baseline was accurately measured using four platinum rods, each of length two *toises* (about 3.9 m). Thereafter he used, where possible, the triangulation points used by Cassini in his 1744 survey of France. Méchain's baseline, of a similar length, and also on a straight section of road was in the Perpignan area. Although Méchain's sector was half the length of Delambre, it included the Pyrenees and hitherto unsurveyed parts of Spain. After the two surveyors met, each computed the other's baseline in order to cross-check their results and they then recomputed the metre as 443.296 *lignes*, notably shorter than the 1795 provisional value of 443.44 *lignes* On 15 November 1798 Delambre and Méchain returned to Paris with their data, having completed the survey. The final value of the *mètre* was defined in 1799 as the computed value from the survey.

- *Historical note:* It soon became apparent that Méchain and Delambre's result (443.296 *lignes*) was slightly too short for the meridional definition of the metre. Méchain had made a small error measuring the latitude of Barcelona, so he remeasured it, but kept the second set of measurements secret.

The French metric system

In June 1799, platinum prototypes were fabricated according to the measured quantities, the *mètre des archives* defined to be a length of 443.296 lignes, and the *kilogramme des archives* defined to be a weight of 18827.15 grains of the *livre poids de marc*, and entered into the French National Archives. In December of that year, the metric system based on them became by law the sole system of weights and measures in France from 1801 until 1812.

Despite the law, the populace continued to use the old measures. In 1812, Napoleon revoked the law and issued one called the *mesures usuelles*, restoring the names and quantities of the customary measures but redefined as round multiples of the metric units, so it was a kind of hybrid system. In 1837, after the collapse of the Napoleonic Empire, the new Assembly reimposed the metric system defined by the laws of 1795 and 1799, to take effect in 1840. The metrication of France took until about 1858 to be completed. Some of the old unit names, especially the *livre*, originally a unit of mass derived from the Roman *libra* (as was the English pound), but now meaning 500 grams, are still in use today.

Development of non-coherent metric systems

At the start of the nineteenth century, the French Academy of Sciences' artefacts for length and mass were the only nascent units of the metric system that were defined in terms of formal standards. Other units based on them, except the *litre* proved to be short-lived. Pendulum clocks that could keep time in seconds had been in use for about 150 years, but their geometries were local to both latitude and altitude, so there was no standard of timekeeping. Nor had a unit of time been recognised as an essential base unit for the derivation of things like force and acceleration. Some quantities of electricity like charge and potential had been identified, but names and interrelationships of units were not yet established. Both Fahrenheit (~1724) and Celsius (~1742) scales of temperature existed, and varied instruments for measuring units or degrees of them. The base/derived unit model had not yet been elaborated, nor was it known how many physical quantities might be inter-related.

A model of interrelated units was first proposed in 1861 by the British Association for the Advancement of Science (BAAS) based on what came to be called the "mechanical" units (length, mass and time). Over the following decades, this foundation enabled mechanical, electrical and thermal units to be correlated.

Time

In 1832 German mathematician Carl-Friedrich Gauss made the first absolute measurements of the Earth's magnetic field using a decimal system based on the use of the millimetre, milligram, and second as the base unit of time. Gauss' second was based on astronomical observations of the rotation of the Earth, and was the sexagesimal second of the ancients: a partitioning of the solar day into two cycles of 12 periods, and each period divided into 60 intervals, and each interval so divided again, so that a second was 1/86,400th of the day. This effectively established a time dimension as a necessary constituent of any useful system of measures, and the astronomical second as the base unit.

Work and energy

In a paper published in 1843, James Prescott Joule first demonstrated a means of measuring the energy transferred between different systems when work is done thereby relating Nicolas Clément's calorie, defined in 1824 as "the amount of heat required to raise the temperature of 1 kg of water from 0 to 1 °C at 1 atmosphere of pressure" to mechanical work. Energy became the unifying concept of nineteenth century science, initially by bringing thermodynamics and mechanics together and later adding electrical technology.

The first structured metric system: CGS

In 1861 a committee of the British Association for the Advancement of Science (BAAS) including William Thomson (later Lord Kelvin), James Clerk Maxwell and James Prescott Joule among its members was tasked with investigating the "Standards of Electrical Resistance". In their first report (1862) they laid the ground rules for their work – the metric system was to be used, measures of electrical energy must have the same units as measures of mechanical energy and two sets of electromagnetic units would have to be derived – an electromagnetic system and an electrostatic system. In the second report (1863) they introduced the concept of a coherent system of units whereby units of length, mass and time were identified as "fundamental units" (now known as *base units*). All other units of measure could be derived (hence *derived units*) from these base units. The metre, gram and second were chosen as base units.

In 1861, before a meeting of the BAAS, Charles Bright and Latimer Clark proposed the names of ohm, volt, and farad in honour of Georg Ohm, Alessandro Volta and Michael Faraday respectively for the practical units based on the CGS absolute system. This was supported by Thomson (Lord Kelvin). The concept of naming units of measure after noteworthy scientists was subsequently used for other units.

In 1873, another committee of the BAAS (which also included Maxwell and Thomson) tasked with "the Selection and

Nomenclature of Dynamical and Electrical Units" recommended using the cgs system of units. The committee also recommended the names of "dyne" and "erg" for the cgs units of force and energy. The cgs system became the basis for scientific work for the next seventy years.

The reports recognised two centimetre–gram–second based systems for electrical units: the Electromagnetic (or absolute) system of units (EMU) and the Electrostatic system of units (ESU).

Thermodynamics

Maxwell and Boltzmann had produced theories describing the inter-relational of temperature, pressure and volume of a gas on a microscopic scale but otherwise, in 1900, there was no understanding of the microscopic nature of temperature.

By the end of the nineteenth century, the fundamental macroscopic laws of thermodynamics had been formulated and although techniques existed to measure temperature using empirical techniques, the scientific understanding of the nature of temperature was minimal.

Convention of the metre

With increasing international adoption of the metre, the shortcomings of the *mètre des Archives* as a standard became ever more apparent. Countries which adopted the metre as a legal measure purchased standard metre bars that were intended to be equal in length to the *mètre des Archives*, but there was no systematic way of ensuring that the countries were actually working to the same standard. The meridional definition, which had been intended to ensure international reproducibility, quickly proved so impractical that it was all but abandoned in favour of the artefact standards, but the *mètre des Archives* (and most of its copies) were "end standards": such standards (bars which are exactly one metre in length) are prone to wear with use, and different standard bars could be expected to wear at different rates.

In 1867, it was proposed that a new international standard metre be created, and the length was taken to be that of the *mètre des Archives* "in the state in which it shall be found". The International Conference on Geodesy in 1867 called for the creation of a new international prototype of the metre and of a system by which national standards could be compared with it. The international prototype would also be a "line standard", that is the metre was defined as the distance between two lines marked on the bar, so avoiding the wear problems of end standards. The French government gave practical support to the creation of an International Metre Commission, which met in Paris in 1870 and again in 1872 with the participation of about thirty countries.

On 20 May 1875 an international treaty known as the *Convention du Mètre* (Metre Convention) was signed by 17 states. This treaty established the following organisations to conduct international activities relating to a uniform system for measurements:

- *Conférence générale des poids et mesures* (CGPM or General Conference on Weights and Measures), an intergovernmental conference of official delegates of member nations and the supreme authority for all actions;

- *Comité international des poids et mesures* (CIPM or International Committee for Weights and Measures), consisting of selected scientists and metrologists, which prepares and executes the decisions of the CGPM and is responsible for the supervision of the International Bureau of Weights and Measures;
- *Bureau international des poids et mesures* (BIPM or International Bureau of Weights and Measures), a permanent laboratory and world centre of scientific metrology, the activities of which include the establishment of the basic standards and scales of the principal physical quantities, maintenance of the international prototype standards and oversight of regular comparisons between the international prototype and the various national standards.

The international prototype of the metre and international prototype of the kilogram were both made from a 90% platinum, 10% iridium alloy which is exceptionally hard and which has good electrical and thermal conductivity properties. The prototype had a special X-shaped (Tresca) cross section to minimise the effects of torsional strain during length comparisons. and the prototype kilograms were cylindrical in shape. The London firm Johnson Matthey delivered 30 prototype metres and 40 prototype kilograms. At the first meeting of the CGPM in 1889 bar No. 6 and cylinder No. X were accepted as the international prototypes. The remainder were either kept as BIPM working copies or distributed to member states as national prototypes.

Following the Convention of the Metre, in 1889 the BIPM had custody of two artefacts – one to define length and the other to define mass. Other units of measure which did not rely on specific artefacts were controlled by other bodies.

Although the definition of the kilogram remained unchanged throughout the 20th century, the 3rd CGPM in 1901 clarified that the kilogram was a unit of mass, not of weight. The original batch of 40 prototypes (adopted in 1889) were supplemented from time to time with further prototypes for use by new signatories to the Metre Convention.

In 1921 the Treaty of the Metre was extended to cover electrical units, with the CGPM merging its work with that of the IEC.

Measurement systems before World War II

The 20th century history of measurement is marked by five periods: the 1901 definition of the coherent MKS system; the intervening 50 years of coexistence of the MKS, cgs and common systems of measures; the 1948 *Practical system of units* prototype of the SI; the introduction of the SI in 1960; and the evolution of the SI in the latter half century.

A coherent system

The need for an independent electromagnetic dimension to resolve the difficulties related to defining such units in terms of length, mass and time was identified by Giorgi in 1901. This led to Giorgi presenting a paper in October 1901 to the congress of the Associazione Elettrotecnica Italiana (A.E.I.) in which he showed that a coherent electro-mechanical system of units could be obtained by adding a fourth base unit of an electrical nature (e.g. ampere, volt or ohm) to the three base units proposed in the 1861 BAAS report. This gave physical dimensions to the constants k_e and k_m and hence also to the electro-mechanical quantities ε_0 (permittivity of free space) and μ_0 (permeability of free space). His work also recognised the relevance of energy in the establishment of a coherent, rational system of units, with the joule as the unit of energy, and the electrical units in the International system of units remaining unchanged. However it took more than thirty years before Giorgi's work was accepted in practice by the IEC.

Systems of measurement in the industrial era

As industry developed around the world, the cgs system of units as adopted by the British Association for the Advancement of Science in 1873 with its plethora of electrical units continued to be the dominant system of measurement, and remained so for at least the next 60 years. The advantages were several: it had a comprehensive set of derived units which, while not quite coherent, were at least homologous; the MKS system lacked a defined unit of electromagnetism at all; the MKS units were inconveniently large for the sciences; customary systems of measures held sway in the United States, Britain and the British empire, and even to some extent in France, the birthplace of the metric system, which inhibited adoption of any competing system. Finally, war, nationalism and other political forces inhibited development of the science favouring a coherent system of units. At the 8th CGPM in 1933 the need to replace the "international" electrical units with "absolute" units was raised. The IEC proposal that Giorgi's 'system', denoted informally as MKSX, be adopted was accepted, but no decision was made as to which electrical unit should be the fourth base unit. In 1935 J. E. Sears, proposed that this should be the ampere, but World War II prevented this being formalised until 1946. The first (and only) follow-up comparison of the national standards with the international prototype of the metre was carried out between 1921 and 1936, and indicated that the definition of the metre was preserved to within 0.2 μm. During this follow-up comparison, the way in which the prototype metre should be measured was more clearly defined—the 1889 definition had defined the metre as being the length of the prototype at the temperature of melting ice, but in 1927 the 7th CGPM extended this definition to specify that the prototype metre shall be "supported on two cylinders of at least one centimetre diameter, symmetrically placed in the same horizontal plane at a distance of 571 mm from each other". The choice of 571 mm represents the Airy points of the prototype—the points at which the bending or droop of the bar is minimised.

Working draft of SI: *Practical system of units*

The 9th CGPM met in 1948, fifteen years after the 8th CGPM. In response to formal requests made by the International

Union of Pure and Applied Physics and by the French government to establish a practical system of units of measure, the CGPM requested the CIPM to prepare recommendations for a single practical system of units of measurement, suitable for adoption by all countries adhering to the Metre Convention. The CIPM's draft proposal was an extensive revision and simplification of the metric unit definitions, symbols and terminology based on the MKS system of units.

In accordance with astronomical observations, the second was set as a fraction of the year 1900. The electromagnetic base unit as required by Giorgi was accepted as the ampere. After negotiations with the CIS and IUPAP, two further units, the degree kelvin and the candela, were also proposed as base units. For the first time the CGPM made recommendations concerning derived units. At the same time the CGPM adopted conventions for the writing and printing of unit symbols and numbers and catalogued the symbols for the most important MKS and CGS units of measure.

Time

Until the advent of the atomic clock, the most reliable timekeeper available to mankind was the Earth's rotation. It was natural therefore that the astronomers under the auspices of the International Astronomical Union (IAU) took the lead in maintaining the standards relating to time. During the 20th century it became apparent that the Earth's rotation was slowing down, resulting in days becoming 1.4 milliseconds longer each century – this was verified by comparing the calculated timings of eclipses of the Sun with those observed in antiquity going back to Chinese records of 763 BC. In 1956 the 10th CGPM instructed the CIPM to prepare a definition of the second; in 1958 the definition was published stating that the second (called an *ephemeris* second) would be calculated by extrapolation using Earth's rotational speed in 1900.

Electrical unit

In accordance with Giorgi's proposals of 1901, the CIPM also recommended that the ampere be the base unit from which electromechanical units would be derived. The definitions for the ohm and volt that had previously been in use were discarded and these units became derived units based on the ampere. In 1946 the CIPM formally adopted a definition of the ampere based on the original EMU definition, and redefined the ohm in terms of other base units. The definitions for absolute electrical system based on the ampere were formalised in 1948. The draft proposed units with these names are very close, but not identical, to the International units.

Temperature

In the Celsius scale from the 18th century, temperature was expressed in degrees Celsius with the definition that ice melted at 0 °C, and at standard atmospheric pressure water boiled at 100 °C. A series of lookup tables defined temperature in terms of inter-related empirical measurements made using various devices. In 1948, definitions relating to temperature had to be clarified. (The degree, as an angular measure, was adopted for general use in a number of countries, so in 1948 the General Conference on Weights and Measures (CGPM) recommended that the degree Celsius, as used for the measurement of temperature, be renamed the degree Celsius.)

At the 9th CGPM, the Celsius temperature scale was renamed the Celsius scale and the scale itself was fixed by defining the triple point of water as 0.01 °C, though the CGPM left the formal definition of absolute zero until the 10th CGPM when the name "Kelvin" was assigned to the absolute temperature scale, and the triple point of water was defined as being 273.16 °K.

Luminosity

Prior to 1937, the International Commission on Illumination (CIE from its French title, the Commission Internationale de l'Eclairage) in conjunction with the CIPM produced a standard for luminous intensity to replace the various national standards. This standard, the candela (cd) which was defined as "the brightness of the full radiator at the temperature of solidification of platinum is 60 new candles per square centimetre" was ratified by the CGPM in 1948.

Derived units

The newly accepted definition of the ampere allowed practical and useful coherent definitions of a set of electromagnetic derived units including farad, henry, watt, tesla, weber, volt, ohm, and coulomb. Two derived units, lux and lumen, were based on the new candela, and one, degree Celsius, equivalent to the degree Kelvin. Five other miscellaneous derived units completed the draft proposal: radian, steradian, hertz, joule and newton.

International System of Units (SI)

In 1952 the CIPM proposed the use of wavelength of a specific light source as the standard for defining length, and in 1960 the CGPM accepted this proposal using radiation corresponding to a transition between specified energy levels of the krypton 86 atom as the new standard for the metre. The standard metre artefact was retired.

In 1960, Giorgi's proposals were adopted as the basis of the *Système International d'Unités* (International System of Units), the SI. This initial definition of the SI included six base units, the metre, kilogram, second, ampere, degree Kelvin and candela, and sixteen coherent derived units.

Evolution of the modern SI

The evolution of the SI after its publication in 1960 has seen the addition of a seventh base unit, the *mole*, and six more derived units, the *pascal* for pressure, the *gray*, *sievert* and *becquerel* for radiation, the *siemens* for electrical conductance, and *katal* for catalytic (enzymatic) activity. Several units have also been redefined in terms of physical constants.

New base and derived units

Over the ensuing years, the BIPM developed and maintained cross-correlations relating various measuring devices such as thermocouples, light spectra and the like to the equivalent temperatures.

The mole was originally known as a gram-atom or a gram-molecule – the amount of a substance measured in grams divided by its atomic weight. Originally chemists and physicists had differing views regarding the definition of the atomic weight – both assigned a value of 16 atomic mass units (amu) to oxygen, but physicists defined oxygen in terms of the O isotope whereas chemists assigned 16 amu to O, O and O isotopes mixed in the proportion that they occur in nature. Finally an agreement between the International Union of Pure and Applied Physics (IUPAP) and the International Union of Pure and Applied Chemistry (IUPAC) brought this duality to an end in 1959/60, both parties agreeing to define the atomic weight of C as being exactly 12 amu. This agreement was confirmed by ISO and in 1969 the CIPM recommended its inclusion in SI as a base unit. This was done in 1971 at the 14th CGPM.

Start of migration to constant definitions

The second major trend in the post-modern SI was the migration of unit definitions in terms of physical constants of nature.

In 1967, at the 13th CGPM the degree Kelvin (°K) was renamed the "kelvin" (K).

Astronomers from the US Naval Observatory (USNO) and the National Physical Laboratory determined a relationship between the frequency of radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom and the estimated rate of rotation of the earth in 1900. Their atomic definition of the second was adopted in 1968 by the 13th CGPM.

By 1975, when the second had been defined in terms of a physical phenomenon rather than the earth's rotation, the CGPM authorised the CIPM to investigate the use of the speed of light as the basis for the definition of the metre. This proposal was accepted in 1983.

The candela definition proved difficult to implement so in 1979, the definition was revised and the reference to the radiation source was replaced by defining the candela in terms of the power of a specified frequency of monochromatic yellowish-green visible light, which is close to the frequency where the human eye, when adapted to bright conditions, has greatest sensitivity.

Kilogram artefact instability

After the metre was redefined in 1960, the kilogram remained the only SI base defined by a physical artefact. During the years that followed the definitions of the base units and particularly the *mise en pratique* to realise these definitions have been refined.

The third periodic recalibration in 1988–1989 revealed that the average difference between the IPK and adjusted baseline for the national prototypes was 50 μg – in 1889 the baseline of the national prototypes had been adjusted so that the difference was zero. As the IPK is the definitive kilogram, there is no way of telling whether the IPK had been losing mass or the national prototypes had been gaining mass.

During the course of the century, the various national prototypes of the kilogram were recalibrated against the international prototype of the kilogram (IPK) and therefore against each other. The initial 1889 starting-value offsets of the national prototypes relative to the IPK were nulled, with any subsequent mass changes being relative to the IPK.

Proposed replacements for the IPK

A number of replacements were proposed for the IPK.

From the early 1990s, the International Avogadro Project worked on creating a 1 kilogram, 94 mm, sphere made of a uniform silicon-28 crystal, with the intention of being able replace the IPK with a physical object which would be precisely reproducible from an exact specification. Due to its precise construction, the Avogadro Project's sphere is likely to be the most precisely spherical object ever created by humans.

Other groups worked on concepts such as creating a reference mass via precise electrodeposition of gold or bismuth atoms, and defining the kilogram in terms of the ampere by relating it to forces generated by electromagnetic repulsion of electric currents.

Eventually, the choices were narrowed down to the use of the Watt balance and the International Avogadro Project sphere.

Ultimately, a decision was made not to create any physical replacement for the IPK, but instead to define all SI units in terms of assigning precise values to a number of physical constants which had previously been measured in terms of the earlier unit definitions.

Redefinition in terms of fundamental constants

- At its 23rd meeting (2007), the CGPM mandated the CIPM to investigate the use of natural constants as the basis for all units of measure rather than the artefacts that were then in use.

The following year this was endorsed by the International Union of Pure and Applied Physics (IUPAP). At a meeting of the CCU held in Reading, United Kingdom, in September 2010, a resolution and draft changes to the SI brochure that were to be presented to the next meeting of the CIPM in October 2010 were agreed in principle. The CIPM meeting of October 2010 found that "the conditions set by the General Conference at its 23rd meeting have not yet been fully met. For this reason the CIPM does not propose a revision of the SI at the present time". The CIPM, however, presented a resolution for consideration at the 24th CGPM (17–21 October 2011) to agree to the new definitions in principle, but not to implement them until the details had been finalised.

In the redefinition, four of the seven SI base units – the kilogram, ampere, kelvin, and mole – were redefined by setting exact numerical values for the Planck constant (h), the elementary electric charge (e), the Boltzmann constant (k_B), and the Avogadro constant (N_A), respectively. The second, metre, and candela were already defined by physical constants and were subject to correction to their definitions. The new definitions aimed to improve the SI without changing the value of any units, ensuring continuity with existing measurements.

This resolution was accepted by the conference, and in addition the CGPM moved the date of the 25th meeting forward from 2015 to 2014. At the 25th meeting on 18 to 20 November 2014, it was found that "despite [progress in the necessary requirements] the data do not yet appear to be sufficiently robust for the CGPM to adopt the revised SI at its 25th meeting", thus postponing the revision to the next meeting in 2018.

Measurements accurate enough to meet the conditions were available in 2017 and the redefinition was adopted at the 26th CGPM (13–16 November 2018), with the changes finally coming into force in 2019, creating a system of definitions which is intended to be stable for the long term.