HISTORY OF TECHNOLOGY

Volume 2

Leon McDaniel

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Chapter 9

Byzantine Inventions

This is a list of Byzantine inventions. The Byzantine or Eastern Roman Empire represented the continuation of the Roman Empire after a part of it collapsed.

Its main characteristics were Roman state traditions, Greek culture and Christian faith.

Architecture

- **Cross-in-square**: The cross-in-square was the dominant architectural form of middle Byzantine churches. Marking a decided departure from the oblong ground plan of the basilica, it has been described as "a type of church that was, in its own way, perfect". The earliest extant example being the Theotokos church in Constantinople (907/908), its development can be traced back with a fair degree of certainty at least to the Nea Ekklesia, consecrated in 880/881.
- **Pendentive dome**: Generally speaking, a pendentive is a construction solution which allows a circular dome to be built atop a rectangular floor plan. While preliminary forms already evolved in Roman dome construction, the first fully developed pendentive dome dates to the reconstruction of the Hagia Sophia in 563. Devised by Isodorus the Younger, the nephew of the first architect Isidore of Miletus, the in-circle

design, with a maximum diameter of 31.24 m, remained unsurpassed until the Renaissance (see Florence Cathedral). The Hagia Sophia became the paradigmatic Orthodox church form and its architectural style was emulated by Turkish mosques a thousand years later.

- **Pointed arch bridge**: The earliest known bridge resting on a pointed arch is the 5th or 6th century AD Karamagara Bridge in Cappadocia. Its single arch of 17 m spanned an affluent of the Euphrates. A Greek inscription, citing from the Bible, runs along one side of its arch rib. The structure is today submerged by the Keban Reservoir.

Warfare

- **Counterweight trebuchet**: The earliest written record of the counterweight trebuchet, a vastly more powerful design than the simple traction trebuchet, appears in the work of the 12th-century historian Niketas Choniates. Niketas describes a stone projector used by future emperor Andronikos I Komnenos at the siege of Zevgminon in 1165. This was equipped with a windlass, an apparatus required neither for the traction nor hybrid trebuchet to launch missiles. Chevedden hypothesizes that the new artillery type was introduced at the 1097 Siege of Nicaea when emperor Alexios I Komnenos, an ally of the besieging crusaders, was reported to have invented new pieces of heavy artillery which deviated from the conventional design and made a deep impression on everyone.

- **Hand-trebuchet**: The hand-trebuchet (*cheiromangana*) was a staff sling mounted on a pole using a lever mechanism to propel projectiles. Basically a portable trebuchet which could be operated by a single man, it was advocated by emperor Nikephoros II Phokas around 965 to disrupt enemy formations in the open field. It was also mentioned in the Taktika of general Nikephoros Ouranos (ca. 1000), and listed in the *Anonymus De obsidione toleranda* as a form of artillery.
- **Greek fire**: The invention and military employment of Greek fire played a crucial role in the defense of the empire against the early onslaught of the Muslim Arabs. Brought to Constantinople by a refugee from Syria by the name of Kallinikos, the incendiary weapon came just in time to save the capital from the Muslim sieges of 674–678 and 717–718, which might have otherwise proven fatal to the Byzantine state.
- Greek fire, referred to by Byzantine chroniclers as "sea fire" or "liquid fire", was primarily a naval weapon, used in ship-to-ship battle against enemy galleys. The exact composition was a well-guarded state secret, to the point that modern scholars continue to debate its ingredients, but the main method of projection is fairly clear, indicating effectively a flame-thrower: The liquid mixture, heated in a brazier and pressurized by means of a pump, was ejected by an operator through a siphon in any direction against the enemy. Alternatively, it

could be poured down from swivel cranes or hurled in pottery grenades.

- Greek fire held a fearsome reputation among Byzantium's numerous enemies who began to field – probably differently composed – combustibles of their own. It was, however, no wonder weapon, but dependent on favourable conditions such as a calm sea and wind coming from behind. When and how the use of Greek fire was discontinued is not exactly known. According to one theory, the Byzantines lost the secret due to over-compartmentalization long before the 1204 sack of Constantinople.
- **Incendiary grenade**: Grenades appeared not long after the reign of Leo III (717–741), when Byzantine soldiers learned that Greek fire could not only be projected by flamethrowers, but also be thrown in stone and ceramic jars. Larger containers were hurled by catapults or trebuchets at the enemy, either ignited before release or set alight by fire arrows after impact. Grenades were later adopted for use by Muslim armies: Vessels of the characteristic spheroconical shape which many authors identify as grenade shells were found over much of the Islamic world, and a possible workshop for grenade production from the 13th century was excavated at the Syrian city of Hama.
- **Flamethrower**: for ship-borne flamethrowers, see Greek fire above. Portable hand-siphons were used in land warfare.

Daily life

- **The Fork:** the fork was originally used as a utensil for picking up and eating food in the 7th century by the nobles of the Byzantine empire. It was later introduced to western Europe through the marriage of Theodora Doukaina Selvo to Domenico Selvo. The story goes that during her wedding feast she used her personal two pronged golden fork to eat some food. The Venetians, having not known of the fork and eating with their hands, considered using the fork blasphemous, "God in his wisdom has provided man with natural forks—his fingers. Therefore it is an insult to him to substitute artificial metal forks for them when eating." claimed one member of the clergy. She would later die of a disease a few years later which the Venetians would claim was the result of her disrespecting God with her fork.
- **Corpus Juris Civilis**: Under the reign of Justinian the Great he initiated reforms that had a clear effect on the evolution of jurisprudence as his Corpus Juris Civilis became the foundation of the jurisprudence in the Western world.
- **Icon**: Icons are images of holy beings such as Jesus, Mary and the saints which, painted according to certain traditional rules, have been playing a pivotal role in Orthodox Church veneration since its early days. The most distinctive Byzantine form are representations on portable wooden panels painted in the Hellenistic techniques of tempera or encaustic. Other varieties include (precious) metal

reliefs or mosaic-style panels set with tesserae of precious stones, gold, silver and ivory. The use of icons was violently opposed during the iconoclastic controversy which dominated much of Byzantium's internal politics in the 8th and 9th centuries, but was finally resumed by the victorious iconodules. Only few early icons have survived the iconoclasm, the most prominent examples being the 6th–7th century collection from Saint Catherine's Monastery.

- **Ship mill**: The historian Procopius records that ship mills were introduced by Belisarius during the siege of Rome (537/538), initially as a makeshift solution. After the Ostrogoths had interrupted the water-supply of the aqueducts on which the city was dependant to run its gristmills, Belisarius ordered riverboats to be fitted with mill gearing; these were moored between bridge piers where the strong current powered the water wheels mounted on the vessel. The innovative use quickly found acceptance among medieval watermillers, reaching Paris and the Frankish Realm only two decades later.
- **The theory of impetus**: The theory was introduced by John Philoponus, and it is the precursor to the concepts of inertia, momentum and acceleration.
- **Hospital**: The concept of hospital as institution to offer medical care and possibility of a cure for the patients due to the ideals of Christian charity, rather than just merely a place to die, appeared in Byzantine Empire.
- **Separation of conjoined twins**: The first known example of separating conjoined twins happened in the Byzantine Empire in the 10th century. A pair of

conjoined twins lived in Constantinople for many years when one of them died, so the surgeons in Constantinople decided to remove the body of the dead one. The result was partly successful as the surviving twin lived three days before dying. The fact that the second person survived for few days after separating him was mentioned a century and half years later again by historians. The next recorded case of separating conjoined twins was 1689 in Germany.

Chapter 10

Technology in the Medieval Islamic World

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

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

Al-Biruni, Avicenna and others described the preparation of hundreds of drugs made from medicinal plants and chemical compounds. Islamic physicists such as Ibn Al-Haytham, Al-

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

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

Context

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

Greek knowledge, including the works of Aristotle, into Arabic. These translations supported advances by scientists across the Islamic world.

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

Fields of inquiry

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

Alchemy and chemistry

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

Astronomy and cosmology

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

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

Botany and agronomy

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

Geography and cartography

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

Mathematics

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

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

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

Medicine

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

Optics and ophthalmology

Optics developed rapidly in this period. By the ninth century, there were works on physiological, geometrical and physical optics. Topics covered included mirror reflection. Hunayn ibn Ishaq (809–873) wrote the book *Ten Treatises on the Eye*; this remained influential in the West until the 17th century.

Abbas ibn Firnas (810–887) developed lenses for magnification and the improvement of vision. Ibn Sahl (c. 940–1000) discovered the law of refraction known as Snell's law. He used the law to produce the first Aspheric lenses that focused light without geometric aberrations.

In the eleventh century Ibn al-Haytham (Alhazen, 965–1040) rejected the Greek ideas about vision, whether the Aristotelian tradition that held that the form of the perceived object entered the eye (but not its matter), or that of Euclid and Ptolemy which held that the eye emitted a ray.

Al-Haytham proposed in his *Book of Optics* that vision occurs by way of light rays forming a cone with its vertex at the center of the eye. He suggested that light was reflected from different surfaces in different directions, thus causing objects to look different.

He argued further that the mathematics of reflection and refraction needed to be consistent with the anatomy of the eye. He was also an early proponent of the scientific method, the concept that a hypothesis must be proved by experiments based on confirmable procedures or mathematical evidence, five centuries before Renaissance scientists.

Pharmacology

Advances in botany and chemistry in the Islamic world encouraged developments in pharmacology. Muhammad ibn Zakarīya Rāzi (Rhazes) (865–915) promoted the medical uses of chemical compounds. Abu al-Qasim al-Zahrawi (Abulcasis) (936–1013) pioneered the preparation of medicines by sublimation and distillation. His *Liber servitoris* provides instructions for preparing "simples" from which were compounded the complex drugs then used. Sabur Ibn Sahl (died 869) was the first physician to describe a large variety of drugs and remedies for ailments. Al-Muwaffaq, in the 10th century, wrote *The foundations of the true properties of Remedies*, describing chemicals such as arsenious oxide and silicic acid. He distinguished between sodium carbonate and potassium carbonate, and drew attention to the poisonous nature of copper compounds, especially copper vitriol, and also of lead compounds. Al-Biruni (973–1050) wrote the *Kitab al-Saydalah* (*The Book of Drugs*), describing in detail the properties of drugs, the role of pharmacy and the duties of the pharmacist. Ibn Sina (Avicenna) described 700 preparations, their properties, their mode of action and their indications.

He devoted a whole volume to simples in *The Canon of Medicine*. Works by Masawaih al-Mardini (c. 925–1015) and by Ibn al-Wafid (1008–1074) were printed in Latin more than fifty times, appearing as *De Medicinis universalibus et particularibus* by Mesue the Younger (died 1015) and as the *Medicamentis simplicibus* by Abenguefit (c. 997 – 1074) respectively. Peter of Abano (1250–1316) translated and added a supplement to the work of al-Mardini under the title *De Veneris*. Ibn al-Baytar (1197–1248), in his *Al-Jami fi al-Tibb*, described a thousand simples and drugs based directly on Mediterranean plants collected along the entire coast between Syria and Spain, for the first time exceeding the coverage provided by Dioscorides in classical times. Islamic physicians such as Ibn Sina described clinical trials for determining the efficacy of medical drugs and substances.

Physics

The fields of physics studied in this period, apart from optics and astronomy which are described separately, are aspects of mechanics: statics, dynamics, kinematics and motion. In the sixth century John Philoponus (c. 490 – c. 570) rejected the Aristotelian view of motion. He argued instead that an object acquires an inclination to move when it has a motive power impressed on it.

In the eleventh century Ibn Sina adopted roughly the same idea, namely that a moving object has force which is dissipated by external agents like air resistance. Ibn Sina distinguished between "force" and "inclination" (*mayl*); he claimed that an object gained *mayl* when the object is in opposition to its natural motion. He concluded that continuation of motion depends on the inclination that is transferred to the object, and that the object remains in motion until the *mayl* is spent. He also claimed that a projectile in a vacuum would not stop unless it is acted upon. That view accords with Newton's first law of motion, on inertia. As a non-Aristotelian suggestion, it was essentially abandoned until it was described as "impetus" by Jean Buridan (c. 1295–1363), who was influenced by Ibn Sina's *Book of Healing*.

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

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

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

Zoology

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

The book was mentioned by Al-Kindī (died 850), and commented on by Avicenna (Ibn Sīnā) in his *The Book of*

Healing. Avempace (Ibn Bājja) and Averroes (Ibn Rushd) commented on and criticised *On the Parts of Animals* and *Generation of Animals*.

Significance

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

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

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

Chapter 11

Medieval Technology

Medieval technology is the technology used in medieval Europe under Christian rule. After the Renaissance of the 12th century, medieval Europe saw a radical change in the rate of new inventions, innovations in the ways of managing traditional means of production, and economic growth. The period saw major technological advances, including the adoption of gunpowder, the invention of vertical windmills, spectacles, mechanical clocks, and greatly improved water mills, building techniques (Gothic architecture, medieval castles), and agriculture in general (three-field crop rotation).

The development of water mills from their ancient origins was impressive, and extended from agriculture to sawmills both for timber and stone. By the time of the *Domesday Book*, most large villages had turnable mills, around 6,500 in England alone. Water-power was also widely used in mining for raising ore from shafts, crushing ore, and even powering bellows.

European technical advancements from the 12th to 14th centuries were either built on long-established techniques in medieval Europe, originating from Roman and Byzantine antecedents, or adapted from cross-cultural exchanges through trading networks with the Islamic world, China, and India. Often, the revolutionary aspect lay not in the act of invention itself, but in its technological refinement and application to political and economic power. Though gunpowder along with other weapons had been started by Chinese, it was the Europeans who developed and perfected its military potential, precipitating European expansion and eventual imperialism in the Modern Era. Also significant in this respect were advances in maritime technology. Advances in shipbuilding included the multi-masted ships with lateen sails, the sternpost-mounted rudder and the skeleton-first hull construction. Along with new navigational techniques such as the dry compass, the Jacob's staff and the astrolabe, these allowed economic and military control of the seas adjacent to Europe and enabled the global navigational achievements of the dawning Age of Exploration.

At the turn to the Renaissance, Gutenberg’s invention of mechanical printing made possible a dissemination of knowledge to a wider population, that would not only lead to a gradually more egalitarian society, but one more able to dominate other cultures, drawing from a vast reserve of knowledge and experience. The technical drawings of late-medieval artist-engineers Guido da Vigevano and Villard de Honnecourt can be viewed as forerunners of later Renaissance artist-engineers such as Taccola or da Vinci.

Civil technologies

The following is a list of some important medieval technologies. The approximate date or first mention of a technology in medieval Europe is given. Technologies were often a matter of cultural exchange and date and place of first inventions are not listed here (see main links for a more complete history of each).

Agriculture

- **Carruca** (6th to 9th centuries)

A type of heavy wheeled plough commonly found in Northern Europe. The device consisted of four major parts. The first part was a coulter at the bottom of the plough. This knife was used to vertically cut into the top sod to allow for the plowshare to work. The plowshare was the second pair of knives which cut the sod horizontally, detaching it from the ground below. The third part was the moldboard, which curled the sod outward. The fourth part of the device was the team of eight oxen guided by the farmer. This type of plough eliminated the need for cross-plowing by turning over the furrow instead of merely pushing it outward. This type of wheeled plough made seed placement more consistent throughout the farm as the blade could be locked in at a certain level relative to the wheels. A disadvantage to this type of plough was its poor maneuverability. Since this equipment was large and led by a small herd of oxen, turning the plough was difficult and time-consuming. This caused many farmers to turn away from traditional square fields and adopt a longer, more rectangular field to ensure maximum efficiency.

Ard (plough) (5th century)

While ploughs have been used since ancient times, during the medieval period plough technology improved rapidly. The medieval plough, constructed from wooden beams, could be yoked to either humans or a team of oxen and pulled through any type of terrain. This allowed for faster clearing of forest lands for agriculture in parts of Northern Europe where the soil contained rocks and dense tree roots. With more food being produced, more people were able to live in these areas.

Horse collar (6th to 9th centuries)

Once oxen started to be replaced by horses on farms and in fields, the yoke became obsolete due to its shape not working well with a horses' posture. The first design for a horse collar was a throat-and-girth-harness. These types of harnesses were unreliable though due to them not being sufficiently set in place. The loose straps were prone to slipping and shifting positions as the horse was working and often caused asphyxiation. Around the eighth century, the introduction of the rigid collar eliminated the problem of choking. The rigid collar was "placed over the horses head and rested on its shoulders. This permitted unobstructed breathing and placed the weight of the plow or wagon where the horse could best support it."

Horseshoes (9th century)

While horses are already able to travel on all terrain without a protective covering on the hooves, horseshoes allowed horses to travel faster along the more difficult terrains. The practice of shoeing horses was initially practiced in the Roman Empire but lost popularity throughout the Middle Ages until around the 11th century. Although horses in the southern lands could easily work while on the softer soil, the rocky soil of the north proved to be damaging to the horses' hooves. Since the north was the problematic area, this is where shoeing horses first became popular. The introduction of gravel roadways was also cause for the popularity of horseshoeing. The loads a shoed horse could take on these roads were significantly higher than one that was barefoot. By the 14th century, not only did horses have shoes, but many farmers were shoeing oxen and donkeys in order to help prolong the life of their hooves. The size and weight of the horseshoe changed significantly over the course of the Middle Ages. In the 10th century, horseshoes were secured by six nails and weighed around one-quarter of a pound, but throughout the years, the shoes grew larger and by the 14th century, the shoes were being secured with eight nails and weighed nearly half a pound.

Crop rotation

Two-field system (8th century)

Crop rotation involved farmers to plant half of the field with a crop while the other half would be fallowed for the season. This was also called the two-field system. This system included the farmers' field being divided into two separate crops. One field would grow a crop while the other was allowed to lie fallow and was used to feed livestock and regain lost nutrients. Every year, the two fields would switch in order to ensure fields did not become nutrient deficient. In the 11th century, this system was introduced into Sweden and spread to become the most popular form of farming. The system of crop rotation is still used today by many farmers, who will grow corn one year in a field and will then grow beans or other legumes in the field the next year, this system is how farmers allow for nutrients to be replenished in the soil.

Three-field system (11th century)

While the two-field system was used by medieval farmers, there was also a different system that was being developed at the same time. Around each village in medieval Europe there were three fields that could be used to grow food. One part holds a spring crop, such as barley or oats, another part holds a winter crop, such as wheat or rye, and the third part is an off-field that is left alone to grow and is used to help feed livestock. By rotating the three crops to a new part of the land after each year, the off-field regains some of the nutrients lost during the growing of the two crops.

This system increases agricultural productivity over the two-field system by only having one-third of the field not being used instead of one half. Another advantage of crop rotation is that many scholars believe it helped increase yields by up to 50%.

Wine press (12th century)

The act of making wine was people stepping on grapes inside of a box and then draining the fruit juice and allowing the fermentation process to begin. During the medieval period the wine press had been constantly evolving into a more modern and efficient machine that would give wine makers more wine with less work.

This device was the first practical means of Pressing (wine) on a plane surface. The wine press was made of a giant wooden basket that was bound together by wooden or metal rings that held the basket together. At the top of the basket was a large disc that would depress the contents in the basket crushing the grapes and making the juice to be fermented. The wine press was an expensive piece of machinery that only the wealthy could afford.

The method of Grape stomping was often used as a less expensive alternative. While white wines required the use of a wine press in order to preserve the color of the wine by removing the juices quickly from the skin, red wine did not need to be pressed until the end of the juice removal process since the color did not matter. Many red wine winemakers used their feet to smash the grapes then used a press to remove any juice that remained in the grape skins.

Qanat (water ducts) (5th century)

Ancient and medieval civilizations needed and used water to grow the human population as well as to partake in daily activities. One of the ways that ancient and medieval people gained access to water was through qanats, which were a water duct system that would bring water from an underground source or river source to villages or cities.

A qanat is a tunnel that is just big enough that a single digger could travel through the tunnel and find the source of water as well as allow for water to travel through the duct system to farm land or villages for irrigation or drinking purposes.

These tunnels had a gradual slope which used gravity to pull the water from either an aquifer or a water well. This system was originally found in middle eastern areas and is still used today in places where surface water is hard to find. Qanats were very helpful in not losing water while being transported as well. The most famous water duct system was the Roman aqueduct system, and medieval inventors used the aqueduct system as a blueprint to make getting water to villages more quickly and easily than diverting rivers. After aqueducts and qanats much other water based technology was created and used in medieval periods including water mills, dams, wells and other such technology for easy access to water.

Architecture and construction

Pendentive architecture (6th century)

A specific spherical form in the upper corners to support a dome. Although the first experimentation was made in the 3rd century, it wasn't until the 6th century in the Byzantine Empire that its full potential was achieved.

Artesian well (1126)

A thin rod with a hard iron cutting edge is placed in the bore hole and repeatedly struck with a hammer, underground water pressure forces the water up the hole without pumping. Artesian wells are named after the town of Artois in France, where the first one was drilled by Carthusian monks in 1126.

Central heating through underfloor channels (9th century)

In the early medieval Alpine upland, a simpler central heating system where heat travelled through underfloor channels from the furnace room replaced the Roman hypocaust at some places. In Reichenau Abbey a network of interconnected underfloor channels heated the 300 m large assembly room of the monks during the winter months. The degree of efficiency of the system has been calculated at 90%.

Rib vault (12th century)

An essential element for the rise of Gothic architecture, rib vaults allowed vaults to be built for the first time over rectangles of unequal lengths. It also greatly facilitated scaffolding and largely replaced the older groin vault.

Chimney (12th century)

The first basic chimney appeared in a Swiss monastery in 820. The earliest true chimney did not appear until the 12th century, with the fireplace appearing at the same time.

Segmental arch bridge (1345)

The Ponte Vecchio in Florence is considered medieval Europe's first stone segmental arch bridge since the end of classical civilizations.

Treadwheel crane (1220s)

The earliest reference to a treadwheel in archival literature is in France about 1225, followed by an illuminated depiction in a manuscript of probably also French origin dating to 1240. Apart from tread-drums, windlasses and occasionally cranks were employed for powering cranes.

Stationary harbour crane (1244)

Stationary harbour cranes are considered a new development of the Middle Ages; its earliest use being documented for Utrecht in 1244. The typical harbour crane was a pivoting structure equipped with double treadwheels. There were two types: wooden gantry cranes pivoting on a central vertical axle and stone tower cranes which housed the windlass and treadwheels with only the jib arm and roof rotating. These cranes were placed on docksides for the loading and unloading of cargo where they replaced or complemented older lifting methods like see-saws, winches and yards. **Slewing cranes** which allowed a rotation of the load and were thus particularly suited for dockside work appeared as early as 1340.

Floating crane

- Beside the stationary cranes, floating cranes which could be flexibly deployed in the whole port basin came into use by the 14th century.

Mast crane

Some harbour cranes were specialised at mounting masts to newly built sailing ships, such as in Gdańsk, Cologne and Bremen.

Wheelbarrow (1170s)

The wheelbarrow proved useful in building construction, mining operations, and agriculture. Literary evidence for the use of wheelbarrows appeared between 1170 and 1250 in north-western Europe. The first depiction is in a drawing by Matthew Paris in the mid-13th century.

Art

Oil paint (by 1125)

As early as the 13th century, oil was used to add details to tempera paintings and paint wooden statues. Flemish painter

Jan van Eyck developed the use of a stable oil mixture for panel painting around 1410.

Clocks

Hourglass (1338)

Reasonably dependable, affordable and accurate measure of time. Unlike water in a clepsydra, the rate of flow of sand is independent of the depth in the upper reservoir, and the instrument is not liable to freeze. Hourglasses are a medieval innovation (first documented in Siena, Italy).

Mechanical clocks (13th to 14th centuries)

A European innovation, these weight-driven clocks were used primarily in clock towers.

Mechanics

Compound crank

The Italian physician Guido da Vigevano combines in his 1335 *Texaurus*, a collection of war machines intended for the recapture of the Holy Land, two simple cranks to form a compound crank for manually powering war carriages and paddle wheel boats. The devices were fitted directly to the vehicle's axle respectively to the shafts turning the paddle wheels.

Metallurgy

Blast furnace (1150–1350)

Cast iron had been made in China since before the 4th century BC. European cast iron first appears in Middle Europe (for instance Lapphyttan in Sweden, Dürstel in Switzerland and the Märkische Sauerland in Germany) around 1150, in some places according to recent research even before 1100. The technique is considered to be an independent European development.

Milling

Ship mill (6th century)

The ship mill is a Byzantine invention, designed to mill grains using hydraulic power. The technology eventually spread to the rest of Europe and was in use until ca. 1800.

Paper mill (13th century)

The first certain use of a water-powered paper mill, evidence for which is elusive in both Chinese and Muslim paper making, dates to 1282.

Rolling mill (15th century)

Used to produce metal sheet of an even thickness. First used on soft, malleable metals, such as lead, gold and tin. Leonardo da Vinci described a rolling mill for wrought iron.

Tidal Mills (6th century)

The earliest tidal mills were excavated on the Irish coast where watermillers knew and employed the two main waterwheel types: a 6th-century tide mill at Killoteran near Waterford was powered by a vertical waterwheel, while the tide changes at Little Island were exploited by a twin-flume horizontal-wheeled mill (c. 630) and a vertical undershot waterwheel alongside it. Another early example is the Nendrum Monastery mill from 787 which is estimated to have developed seven to eight horsepower at its peak.

Vertical windmills (1180s)

Invented in Europe as the pivotable post mill, the first surviving mention of one comes from Yorkshire in England in 1185. They were efficient at grinding grain or draining water. Stationary tower mills were also developed in the 13th century.

Water hammer (12th century at the latest)

Used in metallurgy to forge the metal blooms from bloomeries and Catalan forges, they replaced manual hammerwork. The water hammer was eventually superseded by steam hammers in the 19th century.

Navigation

Dry compass (12th century)

The first European mention of the directional compass is in Alexander Neckam's *On the Natures of Things*, written in Paris around 1190. It was either transmitted from China or the Arabs or an independent European innovation. Dry compass were invented in the Mediterranean around 1300.

Astronomical compass (1269)

The French scholar Pierre de Maricourt describes in his experimental study *Epistola de magnete* (1269) three different compass designs he has devised for the purpose of astronomical observation.

Stern-mounted rudders (1180s)

The first depiction of a pintle-and-gudgeon rudder on church carvings dates to around 1180. They first appeared with cogs in the North and Baltic Seas and quickly spread to Mediterranean.

The iron hinge system was the first stern rudder permanently attached to the ship hull and made a vital contribution to the navigation achievements of the age of discovery and thereafter.

Printing, paper and reading

Movable type printing press (1440s)

Johannes Gutenberg's great innovation was not the printing itself, but instead of using carved plates as in woodblock printing, he used separate letters (*types*) from which the printing plates for pages were made up. This meant the types were recyclable and a page cast could be made up far faster.

Paper (13th century)

Paper was invented in China and transmitted through Islamic Spain in the 13th century. In Europe, the paper-making processes was mechanized by water-powered mills and paper presses (see paper mill).

Rotating bookmark (13th century)

A rotating disc and string device used to mark the page, column, and precise level in the text where a person left off reading in a text. Materials used were often leather, velum, or paper.

Spectacles (1280s)

The first spectacles, invented in Florence, used convex lenses which were of help only to the far-sighted. Concave lenses were not developed prior to the 15th century.

Watermark (1282)

This medieval innovation was used to mark paper products and to discourage counterfeiting. It was first introduced in Bologna, Italy.

Science and learning

Theory of impetus (6th century)

A scientific theory that was introduced by John Philoponus who made criticism of Aristotelian principles of physics, and it served as an inspiration to medieval scholars as well as to Galileo Galilei who ten centuries later, during the Scientific Revolution, extensively cited Philoponus in his works while making the case as to why Aristotelian physics was flawed.

It is the intellectual precursor to the concepts of inertia, momentum and acceleration in classical mechanics.

The first extant treatise of magnetism (13th century)

The first extant treatise describing the properties of magnets was done by Petrus Peregrinus de Maricourt when he wrote *Epistola de magnete*.

Arabic numerals (13th century)

The first recorded mention in Europe was in 976, and they were first widely published in 1202 by Fibonacci with his *Liber Abaci*.

University

The first medieval universities were founded between the 11th and 13th centuries leading to a rise in literacy and learning.

By 1500, the institution had spread throughout most of Europe and played a key role in the Scientific Revolution.

Today, the educational concept and institution has been globally adopted.

Textile industry and garments

Functional button (13th century)

German buttons appeared in 13th-century Germany as an indigenous innovation. They soon became widespread with the rise of snug-fitting clothing.

Horizontal loom (11th century)

Horizontal looms operated by foot-treadles were faster and more efficient.

Silk (6th century)

Manufacture of silk began in Eastern Europe in the 6th century and in Western Europe in the 11th or 12th century. Silk had been imported over the Silk Road since antiquity. The technology of "silk throwing" was mastered in Tuscany in the 13th century. The silk works used waterpower and some regard these as the first mechanized textile mills.

Spinning wheel (13th century)

Brought to Europe probably from India.

Miscellaneous

Chess (1450)

The earliest predecessors of the game originated in 6th-century AD India and spread via Persia and the Muslim world to

Europe. Here the game evolved into its current form in the 15th century.

Forest glass (c. 1000)

This type of glass uses wood ash and sand as the main raw materials and is characterised by a variety of greenish-yellow colours.

Grindstones (834)

Grindstones are a rough stone, usually sandstone, used to sharpen iron. The first rotary grindstone (turned with a leveraged handle) occurs in the *Utrecht Psalter*, illustrated between 816 and 834. According to Hägermann, the pen drawing is a copy of a late-antique manuscript. A second crank which was mounted on the other end of the axle is depicted in the *Luttrell Psalter* from around 1340.

Liquor (12th century)

Primitive forms of distillation were known to the Babylonians, as well as Indians in the first centuries AD. Early evidence of distillation also comes from alchemists working in Alexandria, Roman Egypt, in the 1st century.

The medieval Arabs adopted the distillation process, which later spread to Europe. Texts on the distillation of waters, wine, and other spirits were written in Salerno and Cologne in the twelfth and thirteenth centuries.

Liquor consumption rose dramatically in Europe in and after the mid-14th century, when distilled liquors were commonly used as remedies for the Black Death. These spirits would have had a much lower alcohol content (about 40% ABV) than the alchemists' pure distillations, and they were likely first thought of as medicinal elixirs.

Around 1400, methods to distill spirits from wheat, barley, and rye were discovered.

Thus began the "national" drinks of Europe, including gin (England) and *grappa* (Italy). In 1437, "burned water" (brandy) was mentioned in the records of the County of Katzenelnbogen in Germany.

Magnets (12th century)

Magnets were first referenced in the *Roman d'Enéas*, composed between 1155 and 1160.

Mirrors (1180)

The first mention of a "glass" mirror is in 1180 by Alexander Neckham who said "Take away the lead which is behind the glass and there will be no image of the one looking in."

Illustrated surgical atlas (1345)

Guido da Vigevano (c. 1280 – 1349) was the first author to add illustrations to his anatomical descriptions. His *Anathomia* provides pictures of neuroanatomical structures and techniques such as the dissection of the head by means of trephination, and depictions of the meninges, cerebrum, and spinal cord.

Quarantine (1377)

Initially a 40-day-period, the quarantine was introduced by the Republic of Ragusa as a measure of disease prevention related to the Black Death. It was later adopted by Venice from where the practice spread all around in Europe.

Rat traps (1170s)

The first mention of a rat trap is in the medieval romance *Yvain, the Knight of the Lion* by Chrétien de Troyes.

Military technologies

Armour

Quilted Armour (pre-5th–14th Century)

There was a vast amount of armour technology available through the 5th to 16th centuries. Most soldiers during this time wore padded or quilted armor.

This was the cheapest and most available armor for the majority of soldiers. Quilted armour was usually just a jacket made of thick linen and wool meant to pad or soften the impact of blunt weapons and light blows.

Although, this technology predated the 5th century, it was still extremely prevalent because of the low cost and the weapon technology at the time made the bronze armor of the Greeks and Romans obsolete. Quilted armour was also used in conjunction with other types of armour. Usually worn over or under leather, mail, and later plate armour.

Cuir Bouilli (5th–10th Century)

Hardened leather armour also called Cuir Bouilli was a step up from quilted armour. Made by boiling leather in either water, wax or oil to soften it so it can be shaped, it would then be allowed to dry and become very hard. Large pieces of armour could be made such as breast plates, helmets, and leg guards, but many times smaller pieces would be sewn into the quilting of quilted armour or strips would be sewn together on the outside of a linen jacket. This was not as affordable as the quilted armour but offered much better protection against edged slashing weapons.

Chain Mail (11th–16th Century)

The most common type during the 11th through the 16th centuries was the Hauberk, also known earlier than the 11th century as the Carolingian byrnie. Made of interlinked rings of metal, it sometimes consisted of a coif that covered the head and a tunic that covered the torso, arms, and legs down to the knees.

Chain mail was very effective at protecting against light slashing blows but ineffective against stabbing or thrusting blows. The great advantage was that it allowed a great freedom of movement and was relatively light with significant protection over quilted or hardened leather armour. It was far more expensive than the hardened leather or quilted armour because of the massive amount of labor it required to create. This made it unattainable for most soldiers and only the more wealthy soldiers could afford it. Later, toward the end of the 13th century banded mail became popular. Constructed of washer shaped rings of iron overlapped and woven together by straps of leather as opposed to the interlinked metal rings of chain mail, banded mail was much more affordable to manufacture. The washers were so tightly woven together that it was very difficult penetrate and offered greater protection from arrow and bolt attacks.

Jazerant (11th century)

The Jazerant or Jazeraint was an adaptation of chain mail in which the chain mail would be sewn in between layers of linen or quilted armour. Exceptional protection against light slashing weapons and slightly improved protection against small thrusting weapons, but little protection against large blunt weapons such as maces and axes.

This gave birth to reinforced chain mail and became more prevalent in the 12th and 13th century. Reinforced armour was made up of chain mail with metal plates or hardened leather plates sewn in. This greatly improved protection from stabbing and thrusting blows.

Scale Armour (12th century)

A type of Lamellar armour, was made up entirely of small, overlapping plates. Either sewn together, usually with leather straps, or attached to a backing such as linen, or a quilted armor. Scale armour does not require the labor to produce that chain mail does and therefore is more affordable. It also affords much better protection against thrusting blows and pointed weapons. Though, it is much heavier, more restrictive and impedes free movement.

Plate Armour (14th century)

Plate armour covered the entire body. Although parts of the body were already covered in plate armour as early as 1250, such as the Poleyns for covering the knees and Couters – plates that protected the elbows, the first complete full suit without any textiles was seen around 1410–1430. Components of medieval armour that made up a full suit consisted of a cuirass, a gorget, vambraces, gauntlets, cuisses, greaves, and sabatons held together by internal leather straps.

Improved weaponry such as crossbows and the long bow had greatly increased range and power. This made penetration of the chain mail hauberk much easier and more common. By the mid 1400s most plate was worn alone and without the need of a hauberk. Advances in metal working such as the blast furnace and new techniques for carburizing made plate armour nearly impenetrable and the best armour protection available at the time.

Although plate armour was fairly heavy, because each suit was custom tailored to the wearer, it was very easy to move around in. A full suit of plate armour was extremely expensive and mostly unattainable for the majority of soldiers. Only very wealthy land owners and nobility could afford it. The quality of plate armour increases as more armour makers became more proficient in metal working. A suit of plate armour became a symbol of social status and the best made were personalized with embellishments and engravings. Plate armour saw continued use in battle until the 17th century.

Cavalry

Arched saddle (11th century)

The arched saddle enabled mounted knights to wield lances underarm and prevent the charge from turning into an unintentional pole-vault. This innovation gave birth to true shock cavalry, enabling fighters to charge on full gallop.

Spurs (11th century)

Spurs were invented by the Normans and appeared at the same time as the cantled saddle. They enabled the horseman to control his horse with his feet, replacing the whip and leaving his arms free.

Rowel spurs familiar from cowboy films were already known in the 13th century. Gilded spurs were the ultimate symbol of the knighthood – even today someone is said to "earn his spurs" by proving his or her worthiness.

Stirrup (6th century)

Stirrups were invented by steppe nomads in what is today Mongolia and northern China in the 4th century. They were introduced in Byzantium in the 6th century and in the Carolingian Empire in the 8th. They allowed a mounted knight to wield a sword and strike from a distance leading to a great advantage for mounted cavalry.

Gunpowder weapons

Cannon (1324)

Cannons are first recorded in Europe at the siege of Metz in 1324.

In 1350 Petrarch wrote "these instruments which discharge balls of metal with most tremendous noise and flashes of fire...were a few years ago very rare and were viewed with greatest astonishment and admiration, but now they are become as common and familiar as kinds of arms."

Volley gun

See Ribauldequin.

Corned gunpowder (late 14th century)

First practiced in Western Europe, corning the black powder allowed for more powerful and faster ignition of cannons.

It also facilitated the storage and transportation of black powder. Corning constituted a crucial step in the evolution of gunpowder warfare.

very large-calibre cannon (late 14th century)

Extant examples include the wrought-iron Pumhart von Steyr, Dulle Griet and Mons Meg as well as the cast-bronze Faule Mette and Faule Grete (all from the 15th century).

Mechanical artillery

Counterweight trebuchet (12th century)

Powered solely by the force of gravity, these catapults revolutionized medieval siege warfare and construction of fortifications by hurling huge stones unprecedented distances.

Originating somewhere in the eastern Mediterranean basin, counterweight trebuchets were introduced in the Byzantine Empire around 1100 CE, and was later adopted by the Crusader states and as well by the other armies of Europe and Asia.

Missile weapons

Greek fire (7th century)

An incendiary weapon which could even burn on water is also attributed to the Byzantines, where they installed it on their ships. It played a crucial role in the Byzantine Empire's victory over the Umayyad Caliphate during the 717-718 Siege of Constantinople.

Grenade (8th century)

Rudimentary incendiary grenades appeared in the Byzantine Empire, as the Byzantine soldiers learned that Greek fire, a Byzantine invention of the previous century, could not only be thrown by flamethrowers at the enemy, but also in stone and ceramic jars.

Longbow with massed, disciplined archery (13th century)

Having a high rate of fire and penetration power, the longbow contributed to the eventual demise of the medieval knight class. Used particularly by the English to great effect against the French cavalry during the Hundred Years' War (1337–1453).

Steel crossbow (late 14th century)

European innovation came with several different cocking aids to enhance draw power, making the weapons also the first hand-held mechanical crossbows.

Miscellaneous

Combined arms tactics (14th century)

The battle of Halidon Hill 1333 was the first battle where intentional and disciplined combined arms infantry tactics were employed. The English men-at-arms dismounted aside the archers, combining thus the staying power of super-heavy infantry and striking power of their two-handed weapons with the missiles and mobility of the archers using longbows and shortbows. Combining dismounted knights and men-at-arms with archers was the archetypal Western Medieval battle tactics until the battle of Flodden 1513 and final emergence of firearms.

Chapter 12

Renaissance Technology

Renaissance technology was the set of European artifacts and inventions which spread through the Renaissance period, roughly the 14th century through the 16th century. The era is marked by profound technical advancements such as the printing press, linear perspective in drawing, patent law, double shell domes and bastion fortresses. Sketchbooks from artisans of the period (Taccola and Leonardo da Vinci, for example) give a deep insight into the mechanical technology then known and applied.

Renaissance science spawned the Scientific Revolution; science and technology began a cycle of mutual advancement.

Renaissance technology

Some important Renaissance technologies, including both innovations and improvements on existing techniques:

- mining and metallurgy
- blast furnace enabled iron to be produced in significant quantities
- finery forge enabled pig iron (from the blast furnace) into bar iron (wrought iron)
- slitting mill mechanized the production of iron rods for nailmaking
- smeltmill increased the output of lead over previous methods (bole hill)

Late 14th century

Some of the technologies were the arquebus and the musket.

15th century

The technologies that developed in Europe during the second half of the 15th century were commonly associated by authorities of the time with a key theme in Renaissance thought: the rivalry of the Moderns and the Ancients. Three inventions in particular — the printing press, firearms, and the nautical compass — were indeed seen as evidence that the Moderns could not only compete with the Ancients, but had surpassed them, for these three inventions allowed modern people to communicate, exercise power, and finally travel at distances unimaginable in earlier times.

Crank and connecting rod

The crank and connecting rod mechanism which converts circular into reciprocal motion is of utmost importance for the mechanization of work processes; it is first attested for Roman water-powered sawmills. During the Renaissance, its use is greatly diversified and mechanically refined; now connecting-rods are also applied to double compound cranks, while the flywheel is employed to get these cranks over the 'dead-spot'. Early evidence of such machines appears, among other things, in the works of the 15th-century engineers Anonymous of the Hussite Wars and Taccola. From then on, cranks and connecting rods become an integral part of machine design and are applied in ever more elaborate ways: Agostino Ramelli's *The Diverse and Artifactitious Machines* of 1588 depicts eighteen different applications, a number which rises in the 17th-century *Theatrum Machinarum Novum* by Georg Andreas Böckler to forty-five.

Printing press

The introduction of the mechanical movable type printing press by the German goldsmith Johannes Gutenberg (1398–1468) is widely regarded as the single most important event of the second millennium, and is one of the defining moments of the Renaissance. The Printing Revolution which it sparks throughout Europe works as a modern "agent of change" in the transformation of medieval society.

The mechanical device consists of a screw press modified for printing purposes which can produce 3,600 pages per workday, allowing the mass production of printed books on a proto-industrial scale. By the start of the 16th century, printing presses are operating in over 200 cities in a dozen European countries, producing more than twenty million volumes. By 1600, their output had risen tenfold to an estimated 150 to 200 million copies, while Gutenberg book printing spread from Europe further afield.

The relatively free flow of information transcends borders and induced a sharp rise in Renaissance literacy, learning and education; the circulation of (revolutionary) ideas among the rising middle classes, but also the peasants, threatens the traditional power monopoly of the ruling nobility and is a key factor in the rapid spread of the Protestant Reformation. The dawn of the Gutenberg Galaxy, the era of mass communication, is instrumental in fostering the gradual democratization of knowledge which sees for the first time modern media phenomena such as the press or bestsellers emerging. The prized incunables, which are testimony to the aesthetic taste and high proficient competence of Renaissance book printers, are one lasting legacy of the 15th century.

Parachute

The earliest known parachute design appears in an anonymous manuscript from 1470s Renaissance Italy; it depicts a free-hanging man clutching a crossbar frame attached to a conical canopy. As a safety measure, four straps run from the ends of the rods to a waist belt. Around 1485, a more advanced parachute was sketched by the polymath Leonardo da Vinci in his *Codex Atlanticus* (fol. 381v), which he scales in a more favorable proportion to the weight of the jumper. Leonardo's canopy was held open by a square wooden frame, altering the shape of the parachute from conical to pyramidal. The Venetian inventor Fausto Veranzio (1551–1617) modifies da Vinci's parachute sketch by keeping the square frame, but replacing the canopy with a bulging sail-like piece of cloth. This he realized decelerates the fall more effectively. Claims that Veranzio successfully tested his parachute design in 1617 by jumping from a tower in Venice cannot be substantiated; since he was around 65 years old at the time.

Mariner's astrolabe

The earliest recorded uses of the astrolabe for navigational purposes are by the Portuguese explorers Diogo de Azambuja (1481), Bartholomew Diaz (1487/88) and Vasco da Gama (1497–98) during their sea voyages around Africa.

Dry dock

While dry docks were already known in Hellenistic shipbuilding, these facilities were reintroduced in 1495/96, when Henry VII of England ordered one to be built at the Portsmouth navy base.

16th century

Floating dock

- The earliest known description of a floating dock comes from a small Italian book printed in Venice in 1560, titled *Descrittione dell'artifitiosa machina*. In the booklet, an unknown author asks for the privilege of using a new method for the salvaging of a grounded ship and then proceeds to describe and illustrate his approach. The included woodcut shows a ship flanked by two large floating trestles, forming a roof above the vessel. The ship is pulled in an upright position by a number of ropes attached to the superstructure.

Lifting tower

A lifting tower was used to great effect by Domenico Fontana to relocate the monolithic Vatican obelisk in Rome. Its weight of 361 t was far greater than any of the blocks the Romans are known to have lifted by cranes.

Mining, machinery and chemistry A standard reference for the state of mechanical arts during the Renaissance is given in the mining engineering treatise *De re metallica* (1556), which also contains sections on geology, mining and chemistry. *De re metallica* was the standard chemistry reference for the next 180 years.

Early 17th century

Newspaper

The newspaper is an offspring of the printing press from which the press derives its name. The 16th century sees a rising demand for up-to-date information which can not be covered effectively by the circulating hand-written newssheets. For "gaining time" from the slow copying process, Johann Carolus of Strassburg is the first to publish his German-language *Relation* by using a printing press (1605). In rapid succession, further German newspapers are established in Wolfenbüttel (*Avisa Relation oder Zeitung*), Basel, Frankfurt and Berlin. From 1618 onwards, enterprising Dutch printers take up the practice and begin to provide the English and French market with translated news. By the mid-17th century it is estimated that political newspapers which enjoyed the widest popularity reach up to 250,000 readers in the Holy Roman Empire, around one quarter of the literate population.

Air-gun

In 1607 Bartolomeo Crescentio described an air gun equipped with a powerful spiral spring, a device so complex that it must have had predecessors. In 1610 Mersenne spoke in detail of "sclopeti pneumatici constructio", and four years later Wilkins wrote enthusiastically of "that late ingenious invention the wind-gun" as being "almost equall to our powder-guns". In the 1650s Otto von Guericke, famed for his experiments with vacua and pressures, built the *Madeburger Windbuchse*, one of the technical wonders of its time.

Tools, devices, work processes

15th century

Cranked Archimedes' screw

The German engineer Konrad Kyeser equips in his *Bellifortis* (1405) the Archimedes' screw with a crank mechanism which soon replaces the ancient practice of working the pipe by treading.

Cranked reel

In the textile industry, cranked reels for winding skeins of yarn were introduced in the early 15th century.

Brace

The earliest carpenter's braces equipped with a U-shaped grip, that is with a compound crank, appears between 1420 and 1430 in Flanders.

Cranked well-hoist

The earliest evidence for the fitting of a well-hoist with cranks is found in a miniature of c. 1425 in the German *Hausbuch of the Mendel Foundation.*

Paddle wheel boat powered by crank and connecting rod mechanism. While paddle wheel boats powered by manually turned crankshafts were already conceived of by earlier writers such as Guido da Vigevano and the Anonymous Author of the Hussite Wars, the Italian Roberto Valturio much improves on the design in 1463 by devising a boat with five sets of parallel cranks which are all joined to a single power source by one connecting rod; the idea is also taken up by his compatriot Francesco di Giorgio.

Rotary grindstone with treadle

Evidence for rotary grindstones operated by a crank handle goes back to the Carolingian *Utrecht Psalter*. Around 1480, the crank mechanism is further mechanized by adding a treadle.

Geared hand-mill

The geared hand-mill, operated either with one or two cranks, appears in the 15th century.

16th century

Grenade musket

Two 16th-century German grenade muskets working with a wheellock mechanism are on display in the Bayerisches Nationalmuseum, Munich.

Technical drawings of artist-engineers

The revived scientific spirit of the age can perhaps be best exemplified by the voluminous corpus of technical drawings which the artist-engineers left behind, reflecting the wide variety of interests the Renaissance *homo universalis* pursued. The establishment of the laws of linear perspective by Brunelleschi gave his successors, such as Taccola, Francesco di Giorgio Martini and Leonardo da Vinci, a powerful instrument to depict mechanical devices for the first time in a realistic manner. The extant sketch books give modern historians of science invaluable insights into the standards of technology of the time. Renaissance engineers showed a strong proclivity to experimental study, drawing a variety of technical devices, many of which appeared for the first time in history on paper.

However, these designs were not always intended to be put into practice, and often practical limitations impeded the application of the revolutionary designs. For example, da Vinci's ideas on the conical parachute or the winged flying machine were only applied much later. While earlier scholars showed a tendency to attribute inventions based on their first pictorial appearance to individual Renaissance engineers, modern scholarship is more prone to view the devices as products of a technical evolution which often went back to the Middle Ages.

Chapter 13

Technology in the Ottoman Empire

During its 600-year existence, the Ottoman Empire made significant advances in science and technology, in a wide range of fields including mathematics, astronomy and medicine.

The Islamic Golden Age was traditionally believed to have ended in the thirteenth century, but has been extended to the fifteenth and sixteenth centuries by some, who have included continuing scientific activity in the Ottoman Empire in the west and in Persia and Mughal India in the east.

Education

Advancement of madrasah

The madrasah education institution, which first originated during the Seljuk period, reached its highest point during the Ottoman reign.

Education of Ottoman Women in Medicine

Harems were places within a Sultan's palace where his wives, daughters, and female slaves were expected to stay. However, accounts of teaching young girls and boys here have been recorded. Most education of women in the Ottoman Empire was focused on teaching the women to be good house wives and social etiquette. Although the formal education of women was not popular, female physicians and surgeons were still accounted for. Female physicians were given an informal education instead of a formal one. However, the first properly trained female Turkish physician was Safiye Ali. Ali studied medicine in Germany and opened her own practice in Istanbul in 1922, 1 year before the fall of the Ottoman Empire.

Technical education

Istanbul Technical University has a history that began in 1773. It was founded by Sultan Mustafa III as the Imperial Naval Engineers' School (original name: Mühendishane-i Bahr-i Humayun), and it was originally dedicated to the training of ship builders and cartographers. In 1795 the scope of the school was broadened to train technical military staff to modernize the Ottoman army to match the European standards. In 1845 the engineering department of the school was further developed with the addition of a program devoted to the training of architects. The scope and name of the school were extended and changed again in 1883 and in 1909 the school became a public engineering school which was aimed at training civil engineers who could create new infrastructure to develop the empire.

Sciences

Astronomy

Taqi al-Din later built the Constantinople Observatory of Taqi ad-Din in 1577, where he carried out astronomical observations until 1580. He produced a Zij (named *Unbored Pearl*) and astronomical catalogues that were more accurate than those of his contemporaries, Tycho Brahe and Nicolaus Copernicus. Taqi al-Din was also the first astronomer to employ a decimal point notation in his observations rather than the sexagesimal fractions used by his contemporaries and predecessors. He also made use of Abū Rayhān al-Bīrūnī's method of "three points observation".

In *The Nabk Tree*, Taqi al-Din described the three points as "two of them being in opposition in the ecliptic and the third in any desired place." He used this method to calculate the eccentricity of the Sun's orbit and the annual motion of the apogee, and so did Copernicus before him, and Tycho Brahe shortly afterwards. He also invented a variety of other astronomical instruments, including accurate mechanical astronomical clocks from 1556 to 1580.Due to his observational clock and other more accurate instruments Taqi al-Din's values were more accurate.

After the destruction of the Constantinople observatory of Taqi al-Din in 1580, astronomical activity stagnated in the Ottoman Empire, until the introduction of Copernican heliocentrism in 1660, when the Ottoman scholar Ibrahim Efendi al-Zigetvari Tezkireci translated Noël Duret's French astronomical work (written in 1637) into Arabic.

Geography

Ottoman admiral Piri Reis (Turkish: *Pîrî Reis* or *Hacı Ahmet Muhittin Pîrî Bey*) was a navigator, geographer and cartographer active in the early 1500s. He is known today for his maps and charts collected in his *Kitab-ı Bahriye* (*Book of Navigation*), and for the Piri Reis map, one of the oldest maps of America still in existence.

His book contains detailed information on navigation, as well as accurate charts (for their time) describing the important ports and cities of the Mediterranean Sea. His world map, drawn in 1513, is the oldest known Turkish atlas showing the New World. The map was rediscovered by German theologian Gustav Adolf Deissmann in 1929 in the course of work cataloging items held by the Topkapı Palace library.

Medicine

Medicine in the Ottoman Empire was practiced in nearly all places of society as physicians treated patients in homes, markets, and hospitals. Treatment at these different locations were generally the same, but different modalities of treatment existed throughout the Ottoman Empire. Different methodologies included humoral principles, curative medicine, preventative medicine, and prophetic medicine. Ottoman hospitals also adopted the concept of integralism in which a holistic approach to treatment was used. Considerations of this approach included quality of life and care and treatment of both physical and mental health. The integralistic approach shaped the structure of the Ottoman hospital as each sector and group of workers was dedicated to treating a different aspect of the patient's well-being. All shared the general consensus of treating patients with kindness and gentility, but physicians treated the physical body, and musicians used music therapy to treat the mind. Music was regarded as a powerful healing tune and that different sounds had the ability to create different mental states of health.

One of the original building blocks of early Ottoman medicine was humoralism, and the concept of illness to be a result of disequilibrium among the four humors of the body. The four physiological humors each related to one of the four elements: blood and air, phlegm and water, black bile and earth, yellow bile and fire.

Medicinal treatments in early Ottoman medicine often include the use of foods and beverages. Coffee, taken both medicinally and recreationally, was used to treat stomach problems and indigestion by working as a laxative. The stimulant properties of coffee eventually gained recognition and coffee was used to curb fatigue and exhaustion. The use of coffee in medicinal senses was done more in practice by civilians than hospital professionals.

Hospitals and related health-care institutions were referred to as a variety of names: *dârüşşifâ*, *dârüssıhhâ*, *şifâhâne*, *bîmaristân*, *bîmarhâne*, and *timarhâne*. Hospitals were *vakif* institutions, dedicated to charity and offering care to people of all social classes. The aesthetic aspects of the hospitals, including gardens and architecture, were said to be "healing by design". The hospitals also included hammams, or bathhouses, to treat the patients' humors.

The first Ottoman hospital established was the Faith Complex *dârüşşifâ* in 1470; it closed in 1824. Unique features of the hospital were the separation of patients by sex and the use of music to treat the mentally ill. The Bâyezîd *Dârüşşifâ* was founded in 1488 and is most recognized for its unique architecture that served as an influence an influence in the architecture of later European hospitals. The hospital built by Ayşe Hafsa Sulta in 1522 is recognized as one of the most esteemed hospitals of the Ottoman Empire. The hospital devoted a separate wing for the mentally ill, until later limiting all treatment to only the mentally ill. The *bîmârîstân*'s *medrese* provided medical students with combined theoretical and clinical coursework through hospital internships.

Notable Ottoman medical literature includes the work of the Jewish doctor Mûsâ b. Hamun who wrote one of the first literature primarily about dentistry. Hamun also wrote *Risâle fî Tabâyi'l-Edviye ve İsti'mâlihâ*, which used a combination of Hebrew, Arabic, Greek, and European works to transfer European knowledge of medicine to the Ottoman realm. The writer Ibn Cânî, after noticing the prevalence of tobacco use in Turkey, translated Spanish and Arabic works discussing the use of tobacco leaf in medical treatment.

The physician Ömer b. Sinan el-İznikî's works follow the theme of the Chemical Medicine movement and in his two books, *Kitâb-I Künûz-I Hayâti'l-İnsân* and *Kanûn-I Etibbâ-yi Feylosofân*, enclosing directions for the production of medicines. One of the key contributors to Ottoman medical education was Şânizâde Mehmed Atâullah Efendi, whose *Hamse-I Şânizâde* presented modern European anatomy to Ottoman medicine. In 1873, Cemaleddin Efendi and a group of students from the Imperial Medical School put out the *Lügat-I Tıbbiye*, the first modern medical dictionary written in Turkish. Şerafeddin Sabuncuoğlu was the author of the *Cerrahiyyetu'l-Haniyye* (*Imperial Surgery*), the first illustrated surgical atlas, and the *Mücerrebname* (*On Attemption*). The *Cerrahiyyetu'l-*

Haniyye (*Imperial Surgery*) was the first surgical atlas and the last major medical encyclopedia from the Islamic world. Though his work was largely based on Abu al-Qasim al-Zahrawi's *Al-Tasrif*, Sabuncuoğlu introduced many innovations of his own. Female surgeons were also illustrated for the first time in the *Cerrahiyyetu'l-Haniyye*.

The first modern medical school of the Ottoman empire was the Naval Medical School, or *Tersâne Tıbbiyesi*, established in January 1806. The education of the school was largely European-based, using texts in Italian or French and medical journals published in Europe. Behçet Efendi founded the Imperial Medical School, *Tıbhâne-I Âmire*, of Istanbul in 1827 which was based on the following structural guidelines: the acceptance only of Muslim students, and the teachings would be almost entirely in French. In 1839, after Tanzimat reforms, the school was opened to non-Muslim individuals as well. After this point, non-Muslim students became the majority of graduating class and were better able to adapt and take advantage of the European-based education as many of them already spoke French and were placed into the higher ranking class in the school. The Civilian Medical School (*Mekteb-I Tıbbiye-I Mülkiye*) was founded in 1866 to raise the number of Muslim doctors. The school’s teachings were done in Turkish and focused on training students to become civilian physicians rather than military physicians.

Ottoman medicine in the mid-nineteenth century developed institutions for preventative medicine and public health. A quarantine office and quarantine council, the *Meclis-I Tahaffuz-I Ulâ* were established. The council eventually became an international organization with participation from European countries, the United States, Iran, and Russia. The Ottoman Empire was also home to many institutions organized for the purpose of inoculation vaccination research and investigations. In Istanbul, the İstanbul Rabies and Bacteriological Laboratory was founded in 1877 for research in microbiology and the testing of rabies inoculation. The Smallpox Vaccination Laboratory and the Imperial Vaccination Center were also created in the late nineteenth century.

The first Ottoman hospital, Dar al-Shifa (literally "house of health"), was built in the Ottoman's capital city of Bursa in 1399. This hospital and the ones built after were structured similarly to the ones of the Seljuk Empire, where "even wounded crusaders preferred Muslim doctors as they were very knowledgeable." However, in Ottoman hospitals, mentally ill patients were treated with music therapy in separated buildings that were still part of the hospital complex. Different mental illnesses were treated with different modes of music therapy. Ottoman Empire hospitals were primarily established and used for treating the sick then developed into centers for medical science teaching as well.

Physics

In 1574, Taqi al-Din (1526–1585) wrote the last major Arabic work on optics, entitled Kitab Nūr hadaqat al-ibsār wa-nūr haqīqat al-anzār (Book of the Light of the Pupil of Vision and the Light of the Truth of the Sights), which contains experimental investigations in three volumes on vision, the light's reflection, and the light's refraction. The book deals with the structure of light, its diffusion and global refraction, and the relation between light and colour. In the first volume, he discusses "the nature of light, the source of light, the nature of the propagation of light, the formation of sight, and the effect of light on the eye and sight". In the second volume, he provides "experimental proof of the specular reflection of accidental as well as essential light, a complete formulation of the laws of reflection, and a description of the construction and use of a copper instrument for measuring reflections from plane, spherical, cylindrical, and conical mirrors, whether convex or concave." The third volume "analyses the important question of the variations light undergoes while traveling in mediums having different densities, i.e. the nature of refracted light, the formation of refraction, the nature of images formed by refracted light."

Mechanical technology

In 1559, Taqi al-Din invented a six-cylinder 'Monoblock' pump. It was a hydropowered water-raising machine incorporating valves, suction and delivery pipes, piston rods with lead weights, trip levers with pin joints, and cams on the axle of a water-driven scoop-wheel. His 'Monobloc' pump could also create a partial vacuum.

Mechanical clocks

The Ottoman engineer Taqi al-Din invented a mechanical astronomical clock, capable of striking an alarm at any time specified by the user. He described the clock in his book, *The Brightest Stars for the Construction of Mechanical Clocks* (*Al-Kawākib al-durriyya fī wadh' al-bankāmat al-dawriyya*), published in 1559. Similarly to earlier 15th-century European alarm clocks, his clock was capable of sounding at a specified time, achieved by placing a peg on the dial wheel. At the requested time, the peg activated a ringing device. This clock had three dials which showed the hours, degrees and minutes.

He later designed an observational clock to aid in observations at his Constantinople Observatory of Taqi ad-Din (1577–1580). In his treatise *In The Nabk Tree of the Extremity of Thoughts*, he wrote: "We constructed a mechanical clock with three dials which show the hours, the minutes, and the seconds. We divided each minute into five seconds". This was an important innovation in 16th-century practical astronomy, as at the start of the century clocks were not accurate enough to be used for astronomical purposes.

An example of a watch which measured time in minutes was created by an Ottoman watchmaker, Meshur Sheyh Dede, in 1702.

Steam power

In 1551, Taqi al-Din described an early example of an impulse steam turbine and also noted practical applications for a steam turbine as a prime mover for rotating a spit, predating Giovanni Branca's later impulse steam turbine from 1629. Taqi al-Din described such a device in his book, *Al-Turuq al-saniyya fi al-alat al-ruhaniyya* (*The Sublime Methods of Spiritual Machines*), completed in 1551 AD (959 AH). (See *Steam jack*.)

Ottoman Egyptian industries began moving towards steam power in the early 19th century. In Egypt under Muhammad Ali, industrial manufacturing was initially driven by machinery that relied on traditional energy sources, such as animal power, water wheels, and windmills, which were also the principle energy sources in Western Europe up until around 1870. Under Muhammad Ali of Egypt in the early 19th century, steam engines were introduced to Egyptian industrial manufacturing, with boilers manufactured and installed in industries such as ironworks, textile manufacturing, paper mills, and hulling mills. While there was a lack of coal deposits in Egypt, prospectors searched for coal deposits there, and imported coal from overseas, at similar prices to what imported coal cost in France, until the 1830s, when Egypt gained access to coal sources in Lebanon, which had a yearly coal output of 4,000 tons. Compared to Western Europe, Egypt also had superior agriculture and an efficient transport network through the Nile. Economic historian Jean Batou argues that the necessary economic conditions for rapid industrialization existed in Egypt during the 1820s–1830s, as well as for the adoption of oil as a potential energy source for its steam engines later in the 19th century.

Military

The Ottoman Empire in the 16th century was known for their military power throughout southern Europe and the Middle East. The Harquebus, "also spelled arquebus, also called hackbut, first gun fired from the shoulder, a smoothbore matchlock with a stock resembling that of a rifle". It was also first appeared in the Ottoman Empire and was referred to as a handgun. The German Gun was obtained by the German word "hooked gun".

Ottoman artillery included a number of cannons, most of which were designed by Turkish engineers, in addition to a cannon designed by Hungarian engineer Orban, who had earlier offered his services to the Byzantine Empire emperor Constantine XI. Orban's price for the cannons was high, so the Byzantine emperor of Constantinople was not able to afford it. Mehmed II was determined to win the battle, and used cannons to blast through Constantinople's huge wall during the siege of Constantinople on 6 April 1453.

5.18m. The large gun operated a 635mm caliber rounds and was able to fire marble boulders. To put things into perspective, this round was nearly 6 times larger than the main British tank caliber gun at 120mm. The Dardanelles Gun was still present for duty more than 340 years later in 1807, when a Royal Navy force appeared and commenced the Dardanelles Operation. Turkish forces loaded the ancient relics with propellant and projectiles, then fired them at the British ships. The British squadron suffered 28 casualties from this bombardment.

The musket appeared in the Ottoman Empire by 1465. Damascus steel was used in the production of firearms such as the musket from the 16th century. A musket is a long gun which materialized in the Ottoman Empire by 1465. These were large hand-held guns made out of steel and were capable of penetrating heavy armor; however, these guns by the mid-16th century disappeared because heavy armor declined. There were many more versions of the musket which eventually became known as the rifle. In the 15th century the Ottomans had perfected the musket by creating a gun that used a lever and spring. These were much more easy to use during combat. Eventually the rifle as we know today ended the era of the musket

Turkish arquebuses may have reached China before Portuguese ones. In 1598, Chinese writer Zhao Shizhen described Turkish muskets as being superior to European muskets.

The Chinese military book *Wu Pei Chih* (1621) describes a Turkish musket that, rather than using a matchlock mechanism, instead uses a rack-and-pinion mechanism. On release of the trigger, the two racks return automatically to their original positions. This was the first time a rack-and-pinion mechanism is known to have been used in a firearm, with no evidence of its use in any European or East-Asian firearms at the time.

The Ottoman Empire military was also tactically proficient in the use of small arms weapons such as rifles and handguns. Like many other great powers, the Ottomans issued the M1903 Mauser bolt-action rifle to its most elite front-line infantry and cavalry soldiers, also known as Janissaries. With a five-round box magazine and maximum effective range of 600 meters, the Ottomans were able to effectively engage enemy soldiers when they were unable to utilize field artillery cannons. Second line units, or Jardamas, were primarily issued obsolete single shot weapons such as the M1887 rife, M1874 rifle or older modeled revolvers. Officers in the Ottoman Empire Army were authorized to purchase their own personal handguns from the various number of European craftsmen.

Chapter 14

Great Divergence

The Great Divergence or European miracle is the socioeconomic shift in which the Western world (i.e. Western Europe and the parts of the New World where its people became the dominant populations) overcame pre-modern growth constraints and emerged during the 19th century as the most powerful and wealthy world civilization, eclipsing Mughal India, Qing China, Joseon Korea, and Tokugawa Japan.

Scholars have proposed a wide variety of theories to explain why the Great Divergence happened, including geography, culture, institutions, colonialism, resources and just pure chance. There is disagreement over the nomenclature of the "great" divergence, as a clear point of beginning of a divergence is traditionally held to be the 16th or even the 15th century, with the commercial revolution and the origins of mercantilism and capitalism during the Renaissance and the Age of Discovery, the rise of the European colonial empires, proto-globalization, the Scientific Revolution, or the Age of Enlightenment. Yet the largest jump in the divergence happened in the late 18th and 19th centuries with the Industrial Revolution and Technological Revolution. For this reason, the "California school" considers only this to be the *great* divergence.

Technological advances, in areas such as railroads, steamboats, mining, and agriculture, were embraced to a higher degree in the West than the East during the Great Divergence. Technology led to increased industrialization and economic complexity in the areas of agriculture, trade, fuel and resources, further separating the East and the West. Western Europe's use of coal as an energy substitute for wood in the mid-19th century gave it a major head start in modern energy production. In the twentieth century, the Great Divergence peaked before the First World War and continued until the early 1970s; then, after two decades of indeterminate fluctuations, in the late 1980s it was replaced by the Great Convergence as the majority of Third World countries reached economic growth rates significantly higher than those in most First World countries.

Terminology and definition

The term "Great Divergence" was coined by Samuel P. Huntington in 1996 and used by Kenneth Pomeranz in his book *The Great Divergence: China, Europe, and the Making of the Modern World Economy* (2000). The same phenomenon was discussed by Eric Jones, whose 1981 book *The European Miracle: Environments, Economies and Geopolitics in the History of Europe and Asia* popularized the alternate term "European Miracle". Broadly, both terms signify a socioeconomic shift in which European countries advanced ahead of others during the modern period.

The timing of the Great Divergence is in dispute among historians. The traditional dating is as early as the 16th (or even 15th) century, with scholars arguing that Europe had been on a trajectory of higher growth since that date. Pomeranz and others of the California school argue that the period of most rapid divergence was during the 19th century. Citing nutrition data and chronic European trade deficits as evidence, these scholars argue that before that date the most developed parts of Asia had comparable economic development to Europe, especially China in the Yangzi Delta and India. Some argue that the cultural factors behind the divergence can be traced to earlier periods and institutions such as the Renaissance and the Chinese imperial examination system. Broadberry asserts that even the richest areas of Asia were behind Western Europe as early as the 16th century. He cites statistics comparing England to the Yangzi Delta (the most developed part of China by a good margin) showing that by 1600 the former had three times the latter's average wages when measured in silver, 15% greater wages when measured in wheat equivalent (the latter being used as a proxy for buying power of basic subsistence goods and the former as a proxy for buying power of craft goods, especially traded ones), and higher urbanization. England's silver wages were also five times higher than those of India in the late 16th century, with relatively higher grain wages reflecting an abundance of grain, and low silver wages reflecting low levels of overall development. Grain wages started to diverge more sharply from the early 18th century, with English wages being two and a half times higher than India or China's in wheat equivalent while remaining about five times higher in silver at that time.

Conditions in pre–Great Divergence cores

Unlike modern industrial economies, pre-modern economies were constrained by conditions which greatly limited economic growth. Although core regions in Eurasia had achieved a relatively high standard of living by the 18th century, shortages of land, soil degradation, deforestation, lack of dependable energy sources, and other ecological constraints limited growth in per capita incomes. Rapid rates of depreciation on capital meant that a great part of savings in pre-modern economies were spent on replacing depleted capital, hampering capital accumulation. Massive windfalls of fuel, land, food and other resources were necessary for continued growth and capital accumulation, leading to colonialism. The Industrial Revolution overcame these restraints, allowing rapid, sustained growth in per capita incomes for the first time in human history.

Western Europe

After the Viking, Muslim and Magyar invasions waned in the 10th century, Europe entered a period of prosperity, population growth and territorial expansion known as the High Middle Ages. Trade and commerce revived, with increased specialization between areas and between the countryside and artisans in towns. By the 13th century the best land had been occupied and agricultural income began to fall, though trade and commerce continued to expand, especially in Venice and other northern Italian cities. The 14th century brought a series of calamities: famines, wars, the Black Death and other epidemics. The resulting drop in the population led to falling rents and rising wages, undermining the feudal and manorial relationships that had characterized Medieval Europe.

According to a 2014 study, "there was a 'little divergence' within Europe between 1300 and 1800: real wages in the North Sea area more or less stabilized at the level attained after the

Black Death, and remained relatively high (above subsistence) throughout the early modern period (and into the nineteenth century), whereas real wages in the 'periphery' (in Germany, Italy, and Spain) began to fall after the fifteenth century and returned to some kind of subsistence minimum during the 1500–1800 period. This 'little divergence' in real wages mirrors a similar divergence in GDP per capita: in the 'periphery' of Europe there was almost no per capita growth (or even a decline) between 1500 and 1800, whereas in Holland and England real income continued to rise and more or less doubled in this period."

In the Age of Exploration navigators discovered new routes to the Americas and Asia. Commerce expanded, together with innovations such as joint stock companies and various financial institutions. New military technologies favored larger units, leading to a concentration of power in states whose finances relied on trade. France and Spain developed absolute monarchies reliant on high taxes and state-backed monopolies, leading to economic decline. The Dutch Republic was controlled by merchants, while Parliament gained control of England after a long struggle culminating in the Glorious Revolution. These arrangements proved more hospitable to economic development. At the end of the 16th century, London and Antwerp began pulling away from other European cities, as illustrated in the following graph of real wages in several European cities:

According to a 2021 review of existing evidence by Jack Goldstone, the Great Divergence only arose after 1750 (or even 1800) in northwestern Europe. Prior to that, economic growth rates in northwestern Europe were neither sustained nor remarkable, and income per capita was similar to "peak levels achieved hundreds of years earlier in the most developed regions of Italy and China."

The West had a series of unique advantages compared to Asia, such as the proximity of coal mines; the discovery of the New World, which alleviated ecological restraints on economic growth (land shortages etc.); and the profits from colonization.

China

China had a larger population than Europe throughout the Common Era. Unlike Europe, it was politically united for long periods during that time.

During the Song Dynasty (960–1279), the country experienced a revolution in agriculture, water transport, finance, urbanization, science and technology, which made the Chinese economy the most advanced in the world from about 1100. Mastery of wet-field rice cultivation opened up the hitherto underdeveloped south of the country, while later northern China was devastated by Jurchen and Mongol invasions, floods and epidemics. The result was a dramatic shift in the center of population and industry from the home of Chinese civilization around the Yellow River to the south of the country, a trend only partially reversed by the re-population of the north from the 15th century. By 1300, China as a whole had fallen behind Italy in living standards and by 1400, England had also caught up with it but its wealthiest regions, especially the Yangzi Delta, may have remained on par with those of Europe until the early 18th century.

In the late imperial period (1368–1911), comprising the Ming and Qing dynasties, taxation was low, and the economy and population grew significantly, though without substantial increases in productivity. Chinese goods such as silk, tea and ceramics were in great demand in Europe, leading to an inflow of silver, expanding the money supply and facilitating the growth of competitive and stable markets. By the end of the 18th century, population density levels exceeded those in Europe. China had more large cities but far fewer small ones than in contemporary Europe. Kenneth Pomeranz originally claimed that Great Divergence did not begin until the 19th century. Later he revisited his position and now sees the date between 1700 and 1750.

India

According to a 2020 study and dataset, the Great Divergence between northern India (from Gujarat to Bengal) and Britain began in the late 17th century. It widened after the 1720s and exploded after the 1800s. The study found that it was "primarily England's spurt and India's stagnation in the first half of the nineteenth century that brought about most serious differences in the standard of living."

By the 1500s, India, especially the Bengal Sultanate, a major trading nation in the world, benefited from extensive external and internal trade. Its agriculture was highly efficient as well as its industry. Unlike China, Japan and western and central Europe, India did not experience extensive deforestation until the 19th and 20th centuries. It thus had no pressure to move to coal as a source of energy. From the 17th century, cotton textiles from Mughal India became popular in Europe, with some governments banning them to protect their wool industries. Mughal Bengal, the most developed region, in particular, was globally prominent in industries such as textile manufacturing and shipbuilding.

In early modern Europe, there was significant demand for products from Mughal India, particularly cotton textiles, as well as goods such as spices, peppers, indigo, silks, and saltpeter (for use in munitions). European fashion, for example, became increasingly dependent on Indian textiles and silks. In the 17th and 18th centuries, India accounted for 95% of British imports from Asia, and the Bengal Subah alone accounted for 40% of Dutch imports from Asia.

Amiya Kumar Bagchi estimates 10.3% of Bihar's populace were involved in hand spinning thread, 2.3% weaving, and 9% in other manufacturing trades, in 1809–13, to satisfy this demand. In contrast, there was very little demand for European goods in India, which was largely self-sufficient, thus Europeans had very little to offer, except for some woolen textiles, unprocessed metals and a few luxury items. The trade imbalance caused Europeans to export large quantities of gold and silver to India in order to pay for Indian imports.

Middle East

The Middle East was more advanced than Western Europe in 1000 CE, on par by the middle of the 16th century, but by 1750, leading Middle-Eastern states had fallen behind the leading Western European states of Britain and the Netherlands.

An example of a Middle-Eastern country that had an advanced economy in the early 19th century was Ottoman Egypt, which had a highly productive industrial manufacturing sector, and per-capita income that was comparable to leading Western European countries such as France and higher than that of Japan and Eastern Europe. Other parts of the Ottoman Empire, particularly Syria and southeastern Anatolia, also had a highly productive manufacturing sector that was evolving in the 19th century. In 1819, Egypt under Muhammad Ali began programs of state-sponsored industrialization, which included setting up factories for weapons production, an iron foundry, large-scale cotton cultivation, mills for ginning, spinning and weaving of cotton, and enterprises for agricultural processing. By the early 1830s, Egypt had 30 cotton mills, employing about 30,000 workers. In the early 19th century, Egypt had the world's fifth most productive cotton industry, in terms of the number of spindles per capita.

The industry was initially driven by machinery that relied on traditional energy sources, such as animal power, water wheels, and windmills, which were also the principle energy sources in Western Europe up until around 1870. While steam power had been experimented with in Ottoman Egypt by engineer Taqi ad-Din Muhammad ibn Ma'ruf in 1551, when he invented a steam jack driven by a rudimentary steam turbine, it was under Muhammad Ali of Egypt in the early 19th century that steam engines were introduced to Egyptian industrial manufacturing. Boilers were manufactured and installed in Egyptian industries such as ironworks, textile manufacturing, paper mills, and hulling mills. Compared to Western Europe, Egypt also had superior agriculture and an efficient transport network through the Nile. Economic historian Jean Batou argues that the necessary economic conditions for rapid industrialization existed in Egypt during the 1820s–1830s.

After the death of Muhammad Ali in 1849, his industrialization programs fell into decline, after which, according to historian Zachary Lockman, "Egypt was well on its way to full integration into a European-dominated world market as supplier of a single raw material, cotton."

Lockman argues that, had Egypt succeeded in its industrialization programs, "it might have shared with Japan [or the United States] the distinction of achieving autonomous capitalist development and preserving its independence."

Japan

Japanese society was governed by the Tokugawa Shogunate, which divided Japanese society into a strict hierarchy and intervened considerably in the economy through state monopolies and restrictions on foreign trade; however, in practice, the Shogunate's rule was often circumvented.

From 725 to 1974, Japan experienced GDP per capita growth at an annual rate of 0.04%, with major periods of positive per capita GDP growth occurring during 1150–1280, 1450–1600 and after 1730. There were no significant periods of sustained growth reversals. Relative to the United Kingdom, GDP per capita was at roughly similar levels until the middle of the 17th century. By 1850, per capita incomes in Japan were approximately a quarter of the British level. However, 18th-century Japan had a higher life expectancy, 41.1 years for adult males, compared with 31.6 to 34 for England, between 27.5 and 30 for France, and 24.7 for Prussia.

Korea

In its earlier days, Korea had healthy international trading relationships, receiving merchants from as far as the Middle East. Yet because of its strategic value to its neighboring countries, Korea had been invaded several times during its Goryeo and Joseon eras, starting with the Mongol invasion in the 13th century.

Though repelled due to its strong navy and aid from China, the Japanese invasions in the late 16th century were particularly devastating to the peninsula and it never truly recovered until the modern era. Due to relatively frequent invasions, increased Western colonization of Asia, and the arrival of Christian missionaries, Korea began a long period of isolationism, maintaining diplomatic relationships primarily with China only. For the rest of the Joseon period, the country was marred by economic hardships, peasant revolts, and political factionalism until it was annexed by Japan in the early 20th century.

Sub-Saharan Africa

Pre-colonial Sub-Saharan Africa was politically fragmented, just as early modern Europe was. Africa was however far more sparsely populated than Europe. According to University of Michigan political scientist Mark Dincecco, "the high land/ labor ratio may have made it less likely that historical institutional centralization at the "national level" would occur in sub-Saharan Africa, thwarting further state development." The transatlantic slave trade may have further weakened state power in Africa.

For most of the first millennium AD, the Axumite Kingdom in East Africa had a powerful navy and trading links reaching as far as the Byzantine Empire and India. Between the 14th and 17th centuries, the Ajuran Sultanate in modern-day Somalia practiced hydraulic engineering and developed new systems for agriculture and taxation, which continued to be used in parts of the Horn of Africa as late as the 19th century. On the east coast of Africa, Swahili kingdoms had a prosperous trading empire. Swahili cities were important trading ports along the Indian Ocean, engaging in trade with the Middle East and Far East. A series of states developed in the Sahel on the southern edge of the Sahara which made immense profits from trading across the Sahara, trading heavily in gold and slaves for the Trans-Saharan slave trade. Africa was home to numerous wealthy empires which grew around coastal areas or large rivers that served as part of important trade routes. Kingdoms in the heavily forested regions of West Africa were also part of trade networks. The growth of trade in this area was driven by the Yoruba civilization, which was supported by cities surrounded by farmed land and made wealthy by extensive trade development. Kingdoms in southern Africa also developed extensive trade links with other civilizations as far away as China and India. The institutional framework for long-distance trade across political and cultural boundaries had long been strengthened by the adoption of Islam as a cultural and moral foundation for trust among and with traders.

Possible factors

Scholars have proposed numerous theories to explain why the Great Divergence occurred.

Coal

In metallurgy and steam engines the Industrial Revolution made extensive use of coal and coke – as cheaper, more plentiful and more efficient than wood and charcoal. Coal-fired steam engines also operated in the railways and in shipping, revolutionizing transport in the early 19th century.

Kenneth Pomeranz drew attention to differences in the availability of coal between West and East. Due to regional climate, European coal mines were wetter, and deep mines did not become practical until the introduction of the Newcomen steam engine to pump out groundwater. In mines in the arid northwest of China, ventilation to prevent explosions was much more difficult.

Another difference involved geographic distance; although China and Europe had comparable mining technologies, the distances between the economically developed regions and coal deposits differed vastly. The largest coal deposits in China are located in the northwest, within reach of the Chinese industrial core during the Northern Song (960–1127). During the 11th century China developed sophisticated technologies to extract and use coal for energy, leading to soaring iron production. The southward population shift between the 12th and 14th centuries resulted in new centers of Chinese industry far from the major coal deposits. Some small coal deposits were available locally, though their use was sometimes hampered by government regulations. In contrast, Britain contained some of the largest coal deposits in Europe – all within a relatively compact island.

The centrality of coal to Industrial revolution was criticized by Gregory Clark and David Jacks, who show that coal could be substituted without much loss of national income. Similarly Deirdre N. McCloskey says that coal could easily have been imported to Britain from other countries. Moreover the Chinese could move their industries closer to coal reserves.

New World

A variety of theories posit Europe's unique relationship with the New World as a major cause of the Great Divergence. The high profits earned from the colonies and the slave trade constituted 7 percent a year, a relatively high rate of return considering the high rate of depreciation on pre-industrial capital stocks, which limited the amount of savings and capital accumulation. Early European colonization was sustained by profits through selling New World goods to Asia, especially silver to China. According to Pomeranz, the most important advantage for Europe was the vast amount of fertile, uncultivated land in the Americas which could be used to grow large quantities of farm products required to sustain European economic growth and allowed labor and land to be freed up in Europe for industrialization. New World exports of wood, cotton, and wool are estimated to have saved England the need for 23 to 25 million acres (100,000 km) of cultivated land (by comparison, the total amount of cultivated land in England was just 17 million acres), freeing up immense amounts of resources. The New World also served as a market for European manufactures.

Chen (2012) also suggested that the New World as a necessary factor for industrialization, and trade as a supporting factor causing less developed areas to concentrate on agriculture supporting industrialized regions in Europe.

Political fragmentation

Jared Diamond and Peter Watson argue that a notable feature of Europe's geography was that it encouraged political balkanization, such as having several large peninsulas and natural barriers such as mountains and straits that provided defensible borders. By contrast, China's geography encouraged political unity, with a much smoother coastline and a heartland dominated by two river valleys (Yellow and Yangtze).

In his book *Guns, Germs, and Steel*, Diamond argues that advanced cultures outside Europe had developed in areas whose geography was conducive to large, monolithic, isolated empires. In these conditions policies of technological and social stagnation could persist. He gives the example of China in 1432, when the Xuande Emperor outlawed the building of ocean-going ships, in which China was the world leader at the time. On the other hand, Christopher Columbus obtained sponsorship from Queen Isabella I of Castile for his expedition even though three other European rulers turned it down. As a result, governments that suppressed economic and technological progress soon corrected their mistakes or were out-competed relatively quickly. He argues that these factors created the conditions for more rapid internal superpower change (Spain succeeded by France and then by the United Kingdom) than was possible elsewhere in Eurasia.

Justin Yifu Lin argued that China's large population size proved beneficial in technological advancements prior to the

14th century, but that the large population size was not an important factor in the kind of technological advancements that resulted in the Industrial Revolution. Early technological advancements depended on "learning by doing" (where population size was an important factor, as advances could spread over a large political unit), whereas the Industrial Revolution was the result of experimentation and theory (where population size is less important).

Economic historian Joel Mokyr has argued that political fragmentation (the presence of a large number of European states) made it possible for heterodox ideas to thrive, as entrepreneurs, innovators, ideologues and heretics could easily flee to a neighboring state in the event that the one state would try to suppress their ideas and activities. This is what set Europe apart from the technologically advanced, large unitary empires such as China. China had both a printing press and movable type, yet the industrial revolution would occur in Europe. In Europe, political fragmentation was coupled with an "integrated market for ideas" where Europe's intellectuals used the lingua franca of Latin, had a shared intellectual basis in Europe's classical heritage and the pan-European institution of the Republic of Letters.

Economic historian Tuan-Hwee Sng has argued that the large size of the Chinese state contributed to its relative decline in the 19th century:

The vast size of the Chinese empire created a severe principal–agent problem and constrained how the country was governed. In particular, taxes had to be kept low due to the emperor's weak oversight of his agents and the need to keep corruption in check. The Chinese state's fiscal weaknesses were long masked by its huge tax base. However, economic and demographic expansion in the eighteenth century exacerbated the problems of administrative control. This put a further squeeze on the nation's finances and left China ill-prepared for the challenges of the nineteenth century.

One reason why Japan was able to modernize and adopt the technologies of the West was due to its much smaller size relative to China.

Stanford political scientist Gary W. Cox argues in a 2017 study,

that Europe's political fragmentation interacted with her institutional innovations to foster substantial areas of "economic liberty," where European merchants could organize production freer of central regulation, faced fewer central restrictions on their shipping and pricing decisions, and paid lower tariffs and tolls than their counterparts elsewhere in Eurasia. When fragmentation afforded merchants multiple politically independent routes on which to ship their goods, European rulers refrained from imposing onerous regulations and levying arbitrary tolls, lest they lose mercantile traffic to competing realms. Fragmented control of trade routes magnified the spillover effects of political reforms. If parliament curbed arbitrary regulations and tolls in one realm, then neighboring rulers might have to respond in kind, even if they themselves remained without a parliament. Greater economic liberty, fostered by the interaction of fragmentation and reform, unleashed faster and more inter-connected urban growth.

Other geographic factors

Fernand Braudel of the Annales school of historians argued that the Mediterranean was poor for fishing due to its depth, therefore encouraging long-distance trade. Furthermore, the Alps and other parts of the Alpide belt supplied the coastal regions with fresh migrants from the uplands. This helped the spread of ideas, as did the east-west axis of the Mediterranean which lined up with the prevailing winds and its many archipelagos which together aided navigation, as was also done by the great rivers which brought inland access, all of which further increased immigration. The peninsulas of the Mediterranean also promoted political nationalism which brought international competition.

Testing theories related to geographic endowments economists William Easterly and Ross Levine find evidence that tropics, germs, and crops affect development through institutions. They find no evidence that tropics, germs, and crops affect country incomes directly other than through institutions, nor did they find any effect of policies on development once controls for institutions were implemented.

Innovation

Beginning in the early 19th century, economic prosperity rose greatly in the West due to improvements in technological efficiency, as evidenced by the advent of new conveniences including the railroad, steamboat, steam engine, and the use of coal as a fuel source. These innovations contributed to the Great Divergence, elevating Europe and the United States to high economic standing relative to the East.

It has been argued the attitude of the East towards innovation is one of the other factors that might have played a big role in the West's advancements over the East. According to David Landes, after a few centuries of innovations and inventions, it seemed like the East stopped trying to innovate and began to sustain what they had. They kept nurturing their pre-modern inventions and did not move forward with the modern times. China decided to continue a self-sustaining process of scientific and technological advancement on the basis of their indigenous traditions and achievements. The East's attitude towards innovation showed that they focused more on experience, while the West focused on experimentation. The East did not see the need to improve on their inventions and thus from experience, focused on their past successes. While they did this, the West was focused more on experimentation and trial by error, which led them to come up with new and different ways to improve on existing innovations and create new ones.

Efficiency of markets and state intervention

A common argument is that Europe had more free and efficient markets than other civilizations, which has been cited as a reason for the Great Divergence. In Europe, market efficiency was disrupted by the prevalence of feudalism and mercantilism. Practices such as entail, which restricted land ownership, hampered the free flow of labor and buying and selling of land. These feudal restrictions on land ownership were especially strong in continental Europe. China had a relatively more liberal land market, hampered only by weak customary traditions. Bound labor, such as serfdom and slavery were more prevalent in Europe than in China, even during the Manchu conquest. Urban industry in the West was more restrained by guilds and state-enforced monopolies than in China, where in the 18th century the principal monopolies governed salt and foreign trade through Guangzhou. Pomeranz rejects the view that market institutions were the cause of the Great Divergence, and concludes that China was closer to the ideal of a market economy than Europe.

Economic historian Paul Bairoch presents a contrary argument, that Western countries such as the United States, Britain and Spain did not initially have free trade, but had protectionist policies in the early 19th century, as did China and Japan. In contrast, he cites the Ottoman Empire as an example of a state that did have free trade, which he argues had a negative economic impact and contributed to its deindustrialization. The Ottoman Empire had a liberal trade policy, open to foreign imports, which has origins in capitulations of the Ottoman Empire, dating back to the first commercial treaties signed with France in 1536 and taken further with capitulations in 1673 and 1740, which lowered duties to only 3% for imports and exports. The liberal Ottoman policies were praised by British economists advocating free trade, such as J. R. McCulloch in his *Dictionary of Commerce* (1834), but later criticized by British politicians opposing free trade, such as prime minister Benjamin Disraeli, who cited the Ottoman Empire as "an instance of the injury done by unrestrained competition" in the 1846 Corn Laws debate:

There has been free trade in Turkey, and what has it produced? It has destroyed some of the finest manufactures of the world. As late as 1812 these manufactures existed; but they have been destroyed. That was the consequences of competition in Turkey, and its effects have been as pernicious as the effects of the contrary principle in Spain.

Wages and living standards

Classical economists, beginning with Adam Smith and Thomas Malthus, argued that high wages in the West stimulated labor-saving technological advancements.

Revisionist studies in the mid to late 20th century have depicted living standards in 18th century China and pre-Industrial Revolution Europe as comparable. According to Pomeranz life expectancy in China and Japan was comparable to the advanced parts of Europe.Similarly Chinese consumption per capita in calories intake is comparable to England. According to Pomeranz and others, there was modest per capita growth in both regions, the Chinese economy was not stagnant, and in many areas, especially agriculture, was ahead of Western Europe. Chinese cities were also ahead in public health. Economic historian Paul Bairoch estimated that China's GNP per capita in 1800 was $228 in 1960 US dollars ($1,007 in 1990 dollars), higher than Western Europe's $213 ($941 in 1990 dollars) at the time.

Similarly for Ottoman Egypt, its per-capita income in 1800 was comparable to that of leading Western European countries such as France, and higher than the overall average income of Europe and Japan. Economic historian Jean Barou estimated that, in terms of 1960 dollars, Egypt in 1800 had a per-capita income of $232 ($1,025 in 1990 dollars). In comparison, per-capita income in terms of 1960 dollars for France in 1800 was $240 ($1,060 in 1990 dollars), for Eastern Europe in 1800 was

$177 ($782 in 1990 dollars), and for Japan in 1800 was $180 ($795 in 1990 dollars).

According to Paul Bairoch, in the mid-18th century, "the average standard of living in Europe was a little bit lower than that of the rest of the world." He estimated that, in 1750, the average GNP per capita in the Eastern world (particularly China, India and the Middle East) was $188 in 1960 dollars ($830 in 1990 dollars), higher than the West's $182 ($804 in 1990 dollars). He argues that it was after 1800 that Western European per-capita income pulled ahead. However, the average incomes of China and Egypt were still higher than the overall average income of Europe.

According to Jan Luiten van Zanden, the relationship between GDP per capita with wages and standards of living is very complex. He gives Netherlands economic history as an example. Real wages in Netherlands declined during early modern period between 1450 and 1800. The decline was fastest between 1450/75 and the middle of the sixteenth century, after which real wages stabilized, meaning that even during Dutch Golden Age purchasing power did not grow. The stability remained until middle of 18th century, after which wages declined again. Similarly citing studies of average height of Dutch men, van Zaden shows that it declined from late Middle Ages. During 17th century and 18th, at the height of Dutch golden age the average height was 166 centimeters, about 4 centimeters lower then in 14th and early 15th century. This most likely indicates that consumption declines during early modern period and average height would not equal medieval one until 20th century. Meanwhile, GDP per capita increased by 35 to 55% between 1510/1514 and the 1820s. Hence it is possible that standards of living in advanced parts of Asia were comparable with Western Europe in late 18th century, while Asian GDP per capita was about 70% lower.

Şevket Pamuk and Jan-Luiten van Zanden also shows that, during Industrial revolution, living standards in Western Europe increased little before 1870s, as the increase in nominal wages was undermined by raising food prices. The substantial rise in living standards only started after 1870 with the arrival of cheap food from the America. Western European GDP grew rapidly after 1820 but real wages and standard of living lagged behind.

According to Robert Allen, at the end of the Middle Ages real wages were similar across Europe and at the very high level. In 16th and 17th century wages collapsed everywhere, except in Low Countries and London.These were the most dynamic regions of the early modern economy, and their living standards returned to the high level of the late fifteenth century. The dynamism of London spread to the rest of England in 18th century. Although there was fluctuation in real wages in England between 1500 and 1850, there was no long term rise until last third of 19th century. And it was only after 1870 that real wages begin to rise in other cities of Europe, and only then they finally surpassed the level of late 15th century. Hence while Industrial revolution, raised GDP per capita, it was only a century later before substantial raise in standard of living.

However, responding to the work of Bairoch, Pomeranz, Parthasarathi and others more subsequent research have found that parts of 18th century Western Europe did have higher wages and levels of per capita income than in much of India, Ottoman Turkey, Japan and China. However, the views of Adam Smith were found to have overgeneralized Chinese poverty. Between 1725 and 1825 laborers in Beijing and Delhi were only able to purchase a basket of goods at a subsistence level, while laborers in London and Amsterdam were able to purchase goods at between 4 and 6 times a subsistence level. As early as 1600 Indian GDP per capita was about 60% the British level. A real decline in per capita income did occur in both China and India but in India began during the Mughal period before British colonialism. Outside of Europe much of this decline and stagnation has been attributed to population growth in rural areas outstripping growth in cultivated land as well as internal political turmoil. Free colonials in British North America were considered by historians and economists in a survey of academics to be amongst the most well off people in the world on the eve of the American Revolution. The earliest evidence of a major health transition leading to increased life expectancy began in Europe in the 1770s, approximately one century before Asia's. Robert Allen argues that the relatively high wages in eighteenth century Britain both encouraged the adoption of labour-saving technology and worker training and education, leading to industrialisation.

Luxury consumption

Luxury consumption is regarded by many scholars to have stimulated the development of capitalism and thus contributed to the Great Divergence. Proponents of this view argue that workshops, which manufactured luxury articles for the wealthy, gradually amassed capital to expand their production and then emerged as large firms producing for a mass market;

they believe that Western Europe's unique tastes for luxury stimulated this development further than other cultures. However, others counter that luxury workshops were not unique to Europe; large cities in China and Japan also possessed many luxury workshops for the wealthy, and that luxury workshops do not necessarily stimulate the development of "capitalistic firms".

Property rights

Differences in property rights have been cited as a possible cause of the Great Divergence. This view states that Asian merchants could not develop and accumulate capital because of the risk of state expropriation and claims from fellow kinsmen, which made property rights very insecure compared to those of Europe. However, others counter that many European merchants were de facto expropriated through defaults on government debt, and that the threat of expropriation by Asian states was not much greater than in Europe, except in Japan.

Government and policies are seen as an integral part of modern societies and have played a major role in how different economies have been formed. The Eastern societies had governments which were controlled by the ruling dynasties and thus, were not a separate entity. Their governments at the time lacked policies that fostered innovation and thus resulted in slow advancements. As explained by Cohen, the east had a restrictive system of trade that went against the free world market theory; there was no political liberty or policies that encouraged the capitalist market (Cohen, 1993). This was in contrast to the western society that developed commercial laws and property rights which allowed for the protection and liberty of the marketplace. Their capitalist ideals and market structures encouraged innovation.

Pomeranz (2000) argues that much of the land market in China was free, with many supposedly hereditary tenants and landlords being frequently removed or forced to sell their land. Although Chinese customary law specified that people within the village were to be offered the land first, Pomeranz states that most of the time the land was offered to more capable outsiders, and argues that China actually had a freer land market than Europe.

However, Robert Brenner and Chris Isett emphasize differences in land tenancy rights. They argue that in the lower Yangtze, most farmers either owned land or held secure tenancy at fixed rates of rent, so that neither farmers nor landlords were exposed to competition. In 15th century England, lords had lost their serfs, but were able to assert control over almost all of the land, creating a rental market for tenant farmers. This created competitive pressures against subdividing plots, and the fact that plots could not be directly passed on to sons forced them to delay marriage until they had accumulated their own possessions. Thus in England both agricultural productivity and population growth were subject to market pressures throughout the early modern period.

A 2017 study found that the presence of secure property rights in Europe and their absence in large parts of the Middle-East contributed to the increase of expensive labour-saving capital goods, such as water-mills, windmills, and cranes, in medieval Europe and their decrease in the Middle-East.

High-level equilibrium trap

The high-level equilibrium trap theory argues that China did not undergo an indigenous industrial revolution since its economy was in a stable equilibrium, where supply and demand for labor were equal, disincentivizing the development of labor-saving capital.

European colonialism

A number of economic historians have argued that European colonialism played a major role in the deindustrialization of non-Western societies. Paul Bairoch, for example, cites British colonialism in India as a primary example, but also argues that European colonialism played a major role in the deindustrialization of other countries in Asia, the Middle East, and Latin America, and contributed to a sharp economic decline in Africa. Other modern economic historians have blamed British colonial rule for India's deindustrialization in particular. The colonization of India is seen as a major factor behind both India's deindustrialization and Britain's Industrial Revolution.

The historian Jeffrey G. Williamson has argued that India went through a period of deindustrialization in the latter half of the 18th century as an indirect outcome of the collapse of the Mughal Empire, with British rule later causing further deindustrialization. According to Williamson, the decline of the Mughal Empire led to a decline in agricultural productivity, which drove up food prices, then nominal wages, and then textile prices, which led to India losing a share of the world textile market to Britain even before it had superior factory technology, though Indian textiles still maintained a competitive advantage over British textiles up until the 19th century. Economic historian Prasannan Parthasarathi, however, has argued that there wasn't any such economic decline for several post-Mughal states, notably Bengal Subah and the Kingdom of Mysore, which were comparable to Britain in the late 18th century, until British colonial policies caused deindustrialization.

Up until the 19th century, India was the world's leading cotton textile manufacturer, with Bengal and Mysore the centers of cotton production. In order to compete with Indian imports, Britain invested in labour-saving textile manufacturing technologies during its Industrial Revolution, and following political pressure from the new industrial manufacturers, had the U.K. parliament, in 1813, ended the two centuries old, protectionist East India Company monopoly, on U.K. trade with Asia, that till then had restricted the import of British manufactured goods into the region, and at the same time introducing import tariffs on Indian textiles,. Exposing the Proto-industrial hand spinners and weavers in the territories the British East India Company administered in India to competition from machine spun threads, and woven fabrics, resulting in De-Proto-Industrialization, with the decline of native manufacturing opening up new markets for British goods. British colonization forced open the large Indian market to British goods while restricting Indian imports to Britain, and raw cotton was imported from India without taxes or tariffs to British factories which manufactured textiles from Indian cotton and sold them back to the Indian market. India thus served as both an important supplier of raw goods such as cotton to British factories and a large captive market for

British manufactured goods. In addition, the capital amassed from Bengal following its conquest after the Battle of Plassey in 1757 was used to invest in British industries such as textile manufacturing and greatly increase British wealth. Britain eventually surpassed India as the world's leading cotton textile manufacturer in the 19th century. British colonial rule has been blamed for the subsequently dismal state of British India's economy, with investment in Indian industries limited since it was a colony.

Economic decline in India has been traced to before British colonial rule and was largely a result of increased output in other parts of the world and Mughal disintegration. India's share of world output (24.9%) was largely a function of its share of the world population around 1600. Between 1880 and 1930 total Indian cotton textile production increased from 1200 million yards to 3700 million yards. The introduction of railways into India have been a source of controversy regarding their overall impact, but evidence points to a number of positive outcomes such as higher incomes, economic integration, and famine relief. Per capita GDP decreased from $550 (in 1990 dollars) per person in 1700 under Mughal rule to $533 (in 1990 dollars) in 1820 under British rule, then increased to $618 (in 1990 dollars) in 1947 upon independence. Coal production increased in Bengal, largely to satisfy the demand of the railroads. Life expectancy increased by about 10 years between 1870 and independence.

Recent research on colonialism has been more favorable regarding its long-term impacts on growth and development. A 2001 paper by Daren Acemoglu, Simon Johnson, and James Robinson found that nations with temperate climates and low levels of mortality were more popular with settlers and were subjected to greater degrees of colonial rule. Those nations benefited from Europeans creating more inclusive institutions that lead to higher rates of long term growth. Subsequent research has confirmed that both how long a nation was a colony or how many Europeans settlers migrated there are positively correlated with economic development and institutional quality, although the relationships becomes stronger after 1700 and vary depending on the colonial power, with British colonies typically faring best. Acemoglu et al. also suggest that colonial profits were too small a percentage of GNP to account for the divergence directly but could account for it indirectly due to the effects it had on institutions by reducing the power of absolutist monarchies and securing property rights.

Culture

Rosenberg and Birdzell claim that the so-called "eastern culture" of "respect" and "unquestionable devotion" to the ruling dynasty was as a result of a culture where the control of the dynasty led to a "silent society" that "did not ask questions or experiment without the approval or order from the ruling class". On the other hand, they claimed that the West of the late medieval era did not have a central authority or absolute state, which allowed for a free flow of ideas (Rosenberg, Birdzell, 1986). This so-called "eastern culture" also supposedly showed a "dismissal of change" due to their "fear of failure" and disregard for the imitation of outside inventions and science; this was different from the "western culture" which they claimed to be willing to experiment and imitate others to benefit their society. They claimed that this was a culture where change was encouraged, and sense of anxiety and disregard for comfort led them to be more innovative. Max Weber argued in *The Protestant Ethic and the Spirit of Capitalism* that capitalism in northern Europe evolved when the Protestant work ethic (particularly Calvinist) influenced large numbers of people to engage in work in the secular world, developing their own enterprises and engaging in trade and the accumulation of wealth for investment. In his book *The Religion of China: Confucianism and Taoism* he blames Chinese culture for the non-emergence of capitalism in China. Chen (2012) similarly claims that cultural differences were the most fundamental cause for the divergence, arguing that the Humanism of the Renaissance followed by the Enlightenment (including revolutionary changes in attitude towards religion) enabled a mercantile, innovative, individualistic, and capitalistic spirit. For Ming Dynasty China, he claims there existed repressive measures which stifled dissenting opinions and nonconformity. He claimed that Confucianism taught that disobedience to one's superiors was supposedly tantamount to "sin". In addition Chen claimed that merchants and artificers had less prestige than they did in Western Europe. Justin Yifu Lin has argued for the role of the imperial examination system in removing the incentives for Chinese intellectuals to learn mathematics or to conduct experimentation.

However, many scholars who have studied Confucian teachings have criticized the claim that the philosophy promoted unquestionable loyalty to one's superiors and the state. The core of Confucian philosophy itself was already Humanistic and Rationalistic; it "[does] not share a belief in divine law and [does] not exalt faithfulness to a higher law as a manifestation of divine will."

One of the central teachings of Confucianism is that one should remonstrate with authority. Many Confucians throughout history disputed their superiors in order to not only prevent the superiors and the rulers from wrongdoing, but also to maintain the independent spirits of the Confucians.

Furthermore, the merchant class of China throughout all of Chinese history were usually wealthy and held considerable influence above their supposed social standing. Historians like Yu Yingshi and Billy So have shown that as Chinese society became increasingly commercialized from the Song dynasty onward, Confucianism had gradually begun to accept and even support business and trade as legitimate and viable professions, as long as merchants stayed away from unethical actions. Merchants in the meantime had also benefited from and utilized Confucian ethics in their business practices. By the Song period, the Scholar-officials themselves were using intermediary agents to participate in trading. This is true especially in the Ming-Qing dynasties, when the social status of merchants had risen to such significance that by the late Ming period, many scholar-officials were unabashed to declare publicly in their official family histories that they had family members who were merchants. Consequently, while Confucianism did not actively promote profit seeking, it did not hinder China's commercial development either.

Of the developed cores of the Old world, India was distinguished by its caste system of bound labor, which hampered economic and population growth and resulted in relative underdevelopment compared to other core regions. Compared with other developed regions, India still possessed large amounts of unused resources. India's caste system gave an incentive to elites to drive their unfree laborers harder when faced with increased demand, rather than invest in new capital projects and technology. The Indian economy was characterized by vassal-lord relationships, which weakened the motive of financial profit and the development of markets; a talented artisan or merchant could not hope to gain much personal reward. Pomeranz argues that India was not a very likely site for an industrial breakthrough, despite its sophisticated commerce and technologies.

Aspects of Islamic law have been proposed as an argument for the divergence for the Muslim world. Economist Timur Kuran argues that Islamic institutions which had at earlier stages promoted development later started preventing more advanced development by hampering formation of corporations, capital accumulation, mass production, and impersonal transactions. Other similar arguments proposed include the gradual prohibition of independent religious judgements (Ijtihad) and a strong communalism which limited contacts with outside groups and the development of institutions dealing with more temporary interactions of various kinds, according to Kuran. According to historian Donald Quataert, however, the Ottoman Middle East's manufacturing sector was highly productive and evolving in the 19th century. Quataert criticizes arguments rooted in Orientalism, such as "now-discredited stereotypes concerning the inferiority of Islam", economic institutions having stopped evolving after the Islamic Golden Age, and decline of Ijtihad in religion negatively affecting economic evolution. Economic historian Paul Bairoch noted that Ottoman law promoted liberal free trade earlier than Britain and the United States, arguing that free trade had a negative economic impact on the Ottoman Empire and contributed to its deindustrialization, in contrast to the more protectionist policies of Britain and the United States in the early 19th century.

Representative government

A number of economists have argued that representative government was a factor in the Great Divergence. They argue that absolutist governments, where rulers are not broadly accountable, are bad for property rights and innovation, and that they are prone to corruption and rent-seeking. Representative governments however were accountable to broader segments of the population and thus had to protect property rights and not rule in arbitrary ways, which caused economic prosperity.

Globalization

A 2017 study in the *American Economic Review* found that "globalization was the major driver of the economic divergence between the rich and the poor portions of the world in the years 1850–1900." The states that benefited from globalization were "characterised by strong constraints on executive power, a distinct feature of the institutional environment that has been demonstrated to favour private investment."

Chance

A number of economic historians have posited that the Industrial Revolution may have partly occurred where and when it did due to luck and chance.

Economic effects

The Old World methods of agriculture and production could only sustain certain lifestyles. Industrialization dramatically changed the European and American economy and allowed it to attain much higher levels of wealth and productivity than the other Old World cores. Although Western technology later spread to the East, differences in uses preserved the Western lead and accelerated the Great Divergence.

Productivity

When analyzing comparative use-efficiency, the economic concept of total factor productivity (TFP) is applied to quantify differences between countries. TFP analysis controls for differences in energy and raw material inputs across countries and is then used to calculate productivity. The difference in productivity levels, therefore, reflects efficiency of energy and raw materials use rather than the raw materials themselves. TFP analysis has shown that Western countries had higher TFP levels on average in the 19th century than Eastern countries such as India or China, showing that Western productivity had surpassed the East.

Per capita income

Some of the most striking evidence for the Great Divergence comes from data on per capita income. The West's rise to power directly coincides with per capita income in the West surpassing that in the East. This change can be attributed largely to the mass transit technologies, such as railroads and steamboats, that the West developed in the 19th century. The construction of large ships, trains, and railroads greatly increased productivity. These modes of transport made moving large quantities of coal, corn, grain, livestock and other goods across countries more efficient, greatly reducing transportation costs. These differences allowed Western productivity to exceed that of other regions.

His estimates show that the GDP per capita of Western European countries rose rapidly after industrialization.

For the 18th century, and in comparison to non-European regions, Bairoch in 1995 stated that, in the mid-18th century, "the average standard of living in Europe was a little bit lower than that of the rest of the world."

Agriculture

Before and during the early 19th century, much of continental European agriculture was underdeveloped compared to Asian Cores and England. This left Europe with abundant idle natural resources. England, on the other hand, had reached the limit of its agricultural productivity well before the beginning of the 19th century. Rather than taking the costly route of improving soil fertility, the English increased labor productivity by industrializing agriculture. From 1750 to 1850, European nations experienced population booms; however, European agriculture was barely able to keep pace with the dietary needs. Imports from the Americas, and the reduced caloric intake required by industrial workers compared to farmers allowed England to cope with the food shortages. By the turn of the 19th century, much European farmland had been eroded and depleted of nutrients. Fortunately, through improved farming techniques, the import of fertilizers, and reforestation, Europeans were able to recondition their soil and prevent food shortages from hampering industrialization. Meanwhile, many other formerly hegemonic areas of the world were struggling to feed themselves – notably China.

Fuel and resources

The global demand for wood, a major resource required for industrial growth and development, was increasing in the first half of the 19th century. A lack of interest of silviculture in Western Europe, and a lack of forested land, caused wood shortages.

By the mid-19th century, forests accounted for less than 15% of land use in most Western European countries. Fuel costs rose sharply in these countries throughout the 18th century and many households and factories were forced to ration their usage, and eventually adopt forest conservation policies. It was not until the 19th century that coal began providing much needed relief to the European energy shortage. China had not begun to use coal on a large scale until around 1900, giving Europe a huge lead on modern energy production.

Through the 19th century, Europe had vast amounts of unused arable land with adequate water sources. However, this was not the case in China; most idle lands suffered from a lack of water supply, so forests had to be cultivated. Since the mid-19th century, northern China's water supplies have been declining, reducing its agricultural output. By growing cotton for textiles, rather than importing, China exacerbated its water shortage. During the 19th century, supplies of wood and land decreased considerably, greatly slowing growth of Chinese per capita incomes.

Trade

During the era of European imperialism, periphery countries were often set up as specialized producers of specific resources. Although these specializations brought the periphery countries temporary economic benefit, the overall effect inhibited the industrial development of periphery territories. Cheaper resources for core countries through trade deals with specialized periphery countries allowed the core countries to advance at a much greater pace, both economically and industrially, than the rest of the world.

Europe's access to a larger quantity of raw materials and a larger market to sell its manufactured goods gave it a distinct advantage through the 19th century. In order to further industrialize, it was imperative for the developing core areas to acquire resources from less densely populated areas, since they lacked the lands required to supply these resources themselves. Europe was able to trade manufactured goods to their colonies, including the Americas, for raw materials. The same sort of trading could be seen throughout regions in China and Asia, but colonization brought a distinct advantage to the West. As these sources of raw materials began to proto-industrialize, they would turn to import substitution, depriving the hegemonic nations of a market for their manufactured goods. Since European nations had control over their colonies, they were able to prevent this from happening. Britain was able to use import substitution to its benefit when dealing with textiles from India. Through industrialization, Britain was able to increase cotton productivity enough to make it lucrative for domestic production, and overtake India as the world's leading cotton supplier. Although Britain had limited cotton imports to protect its own industries, they allowed cheap British products into colonial India from the early 19th century. The colonial administration failed to promote Indian industry, preferring to export raw materials.

Western Europe was also able to establish profitable trade with Eastern Europe. Countries such as Prussia, Bohemia and Poland had very little freedom in comparison to the West; forced labor left much of Eastern Europe with little time to work towards proto-industrialization and ample manpower to generate raw materials.

Guilds and journeymanship

A 2017 study in the *Quarterly Journal of Economics* argued, "medieval European institutions such as guilds, and specific features such as journeymanship, can explain the rise of Europe relative to regions that relied on the transmission of knowledge within closed kinship systems (extended families or clans)". Guilds and journeymanship were superior for creating and disseminating knowledge, which contributed to the occurrence of the Industrial Revolution in Europe.

Chapter 15

Industrial Revolution

The Industrial Revolution was the transition to new manufacturing processes in Europe and the United States, in the period from between 1760 to 1820 and 1840. This transition included going from hand production methods to machines, new chemical manufacturing and iron production processes, the increasing use of steam power and water power, the development of machine tools and the rise of the mechanized factory system. The Industrial Revolution also led to an unprecedented rise in the rate of population growth.

Textiles were the dominant industry of the Industrial Revolution in terms of employment, value of output and capital invested. The textile industry was also the first to use modern production methods.

The Industrial Revolution began in Great Britain, and many of the technological innovations were of British origin. By the mid-18th century Britain was the world's leading commercial nation, controlling a global trading empire with colonies in North America and the Caribbean, and with major military and political hegemony on the Indian subcontinent, particularly with the proto-industrialised Mughal Bengal, through the activities of the East India Company. The development of trade and the rise of business were among the major causes of the Industrial Revolution.

The Industrial Revolution marks a major turning point in history; almost every aspect of daily life was influenced in some way. In particular, average income and population began to exhibit unprecedented sustained growth. Some economists have said the most important effect of the Industrial Revolution was that the standard of living for the general population in the western world began to increase consistently for the first time in history, although others have said that it did not begin to meaningfully improve until the late 19th and 20th centuries.

GDP per capita was broadly stable before the Industrial Revolution and the emergence of the modern capitalist economy, while the Industrial Revolution began an era of per-capita economic growth in capitalist economies. Economic historians are in agreement that the onset of the Industrial Revolution is the most important event in the history of humanity since the domestication of animals and plants.

The precise start and end of the Industrial Revolution is still debated among historians, as is the pace of economic and social changes. Eric Hobsbawm held that the Industrial Revolution began in Britain in the 1780s and was not fully felt until the 1830s or 1840s, while T. S. Ashton held that it occurred roughly between 1760 and 1830. Rapid industrialization first began in Britain, starting with mechanized spinning in the 1780s, with high rates of growth in steam power and iron production occurring after 1800. Mechanized textile production spread from Great Britain to continental Europe and the United States in the early 19th century, with important centres of textiles, iron and coal emerging in Belgium and the United States and later textiles in France.

An economic recession occurred from the late 1830s to the early 1840s when the adoption of the Industrial Revolution's early innovations, such as mechanized spinning and weaving, slowed and their markets matured. Innovations developed late in the period, such as the increasing adoption of locomotives, steamboats and steamships, hot blast iron smelting and new technologies, such as the electrical telegraph, widely introduced in the 1840s and 1850s, were not powerful enough to drive high rates of growth. Rapid economic growth began to occur after 1870, springing from a new group of innovations in what has been called the Second Industrial Revolution. These innovations included new steel making processes, mass-production, assembly lines, electrical grid systems, the large-scale manufacture of machine tools and the use of increasingly advanced machinery in steam-powered factories.

Requirements

Six factors facilitated industrialization: high levels of agricultural productivity to provide excess manpower and food; a pool of managerial and entrepreneurial skills; available ports, rivers, canals and roads to cheaply move raw materials and outputs; natural resources such as coal, iron and waterfalls; political stability and a legal system that supported business; and financial capital available to invest. Once industrialization began in Great Britain, new factors can be added: the eagerness of British entrepreneurs to export industrial expertise and the willingness to import the process. Britain met the criteria and industrialized starting in the 18th century. Britain exported the process to western Europe (especially Belgium, France and the German states) in the early

19th century. The United States copied the British model in the early 19th century and Japan copied the Western European models in the late 19th century.

Important technological developments

The commencement of the Industrial Revolution is closely linked to a small number of innovations, beginning in the second half of the 18th century. By the 1830s the following gains had been made in important technologies:

- **Textiles** – mechanised cotton spinning powered by steam or water increased the output of a worker by a factor of around 500. The power loom increased the output of a worker by a factor of over 40. The cotton gin increased productivity of removing seed from cotton by a factor of 50. Large gains in productivity also occurred in spinning and weaving of wool and linen, but they were not as great as in cotton.
- **Steam power** – the efficiency of steam engines increased so that they used between one-fifth and one-tenth as much fuel. The adaptation of stationary steam engines to rotary motion made them suitable for industrial uses. The high pressure engine had a high power to weight ratio, making it suitable for transportation. Steam power underwent a rapid expansion after 1800.
- **Iron making** – the substitution of coke for charcoal greatly lowered the fuel cost of pig iron and wrought iron production. Using coke also allowed larger blast

furnaces, resulting in economies of scale. The steam engine began being used to pump water and to power blast air in the mid 1750s, enabling a large increase in iron production by overcoming the limitation of water power. The cast iron blowing cylinder was first used in 1760. It was later improved by making it double acting, which allowed higher blast furnace temperatures. The puddling process produced a structural grade iron at a lower cost than the finery forge. The rolling mill was fifteen times faster than hammering wrought iron. Hot blast (1828) greatly increased fuel efficiency in iron production in the following decades.

- **Invention of machine tools** – The first machine tools were invented. These included the screw cutting lathe, cylinder boring machine and the milling machine. Machine tools made the economical manufacture of precision metal parts possible, although it took several decades to develop effective techniques.

Textile manufacture

In 1750 Britain imported 2.5 million pounds of raw cotton, most of which was spun and woven by cottage industry in Lancashire. The work was done by hand in workers' homes or occasionally in shops of master weavers.

In 1787 raw cotton consumption was 22 million pounds, most of which was cleaned, carded and spun on machines. The British textile industry used 52 million pounds of cotton in 1800, which increased to 588 million pounds in 1850.

The share of value added by the cotton textile industry in Britain was 2.6% in 1760, 17% in 1801 and 22.4% in 1831. Value added by the British woollen industry was 14.1% in 1801. Cotton factories in Britain numbered approximately 900 in 1797. In 1760 approximately one-third of cotton cloth manufactured in Britain was exported, rising to two-thirds by 1800. In 1781 cotton spun amounted to 5.1 million pounds, which increased to 56 million pounds by 1800. In 1800 less than 0.1% of world cotton cloth was produced on machinery invented in Britain. In 1788 there were 50,000 spindles in Britain, rising to 7 million over the next 30 years.

Wages in Lancashire, a core region for cottage industry and later factory spinning and weaving, were about six times those in India in 1770, when overall productivity in Britain was about three times higher than in India.

Cotton

Parts of India, China, Central America, South America and the Middle-East have a long history of hand manufacturing cotton textiles, which became a major industry sometime after 1000 AD. In tropical and subtropical regions where it was grown, most was grown by small farmers alongside their food crops and was spun and woven in households, largely for domestic consumption. In the 15th century China began to require households to pay part of their taxes in cotton cloth. By the 17th century almost all Chinese wore cotton clothing. Almost everywhere cotton cloth could be used as a medium of exchange. In India a significant amount of cotton textiles were manufactured for distant markets, often produced by professional weavers. Some merchants also owned small weaving workshops. India produced a variety of cotton cloth, some of exceptionally fine quality.

Cotton was a difficult raw material for Europe to obtain before it was grown on colonial plantations in the Americas. The early Spanish explorers found Native Americans growing unknown species of excellent quality cotton: sea island cotton (*Gossypium barbadense*) and upland green seeded cotton *Gossypium hirsutum*. Sea island cotton grew in tropical areas and on barrier islands of Georgia and South Carolina, but did poorly inland. Sea island cotton began being exported from Barbados in the 1650s.

Upland green seeded cotton grew well on inland areas of the southern U.S., but was not economical because of the difficulty of removing seed, a problem solved by the cotton gin. A strain of cotton seed brought from Mexico to Natchez, Mississippi in 1806 became the parent genetic material for over 90% of world cotton production today; it produced bolls that were three to four times faster to pick.

Trade and textiles

The Age of Discovery was followed by a period of colonialism beginning around the 16th century. Following the discovery of a trade route to India around southern Africa by the Portuguese, the Dutch established the Verenigde Oostindische Compagnie (abbr. VOC) or Dutch East India Company, the world's first transnational corporation and the first multinational enterprise to issue shares of stock to the public. The British later founded the East India Company, along with smaller companies of different nationalities which established trading posts and employed agents to engage in trade throughout the Indian Ocean region and between the Indian Ocean region and North Atlantic Europe.

One of the largest segments of this trade was in cotton textiles, which were purchased in India and sold in Southeast Asia, including the Indonesian archipelago, where spices were purchased for sale to Southeast Asia and Europe.

By the mid-1760s cloth was over three-quarters of the East India Company's exports. Indian textiles were in demand in North Atlantic region of Europe where previously only wool and linen were available; however, the amount of cotton goods consumed in Western Europe was minor until the early 19th century.

Pre-mechanized European textile production

By 1600 Flemish refugees began weaving cotton cloth in English towns where cottage spinning and weaving of wool and linen was well established; however, they were left alone by the guilds who did not consider cotton a threat. Earlier European attempts at cotton spinning and weaving were in 12th-century Italy and 15th-century southern Germany, but these industries eventually ended when the supply of cotton was cut off. The Moors in Spain grew, spun and wove cotton beginning around the 10th century.

British cloth could not compete with Indian cloth because India's labour cost was approximately one-fifth to one-sixth that of Britain's. In 1700 and 1721 the British government passed Calico Acts in order to protect the domestic woollen and linen industries from the increasing amounts of cotton fabric imported from India. The demand for heavier fabric was met by a domestic industry based around Lancashire that produced fustian, a cloth with flax warp and cotton weft. Flax was used for the warp because wheel-spun cotton did not have sufficient strength, but the resulting blend was not as soft as 100% cotton and was more difficult to sew.

On the eve of the Industrial Revolution, spinning and weaving were done in households, for domestic consumption and as a cottage industry under the putting-out system. Occasionally the work was done in the workshop of a master weaver. Under the putting-out system, home-based workers produced under contract to merchant sellers, who often supplied the raw materials. In the off season the women, typically farmers' wives, did the spinning and the men did the weaving. Using the spinning wheel, it took anywhere from four to eight spinners to supply one hand loom weaver.

Invention of textile machinery

The flying shuttle, patented in 1733 by John Kay, with a number of subsequent improvements including an important one in 1747, doubled the output of a weaver, worsening the imbalance between spinning and weaving. It became widely used around Lancashire after 1760 when John's son, Robert, invented the drop box, which facilitated changing thread colors.

Lewis Paul patented the roller spinning frame and the flyer-and-bobbin system for drawing wool to a more even thickness. The technology was developed with the help of John Wyatt of Birmingham. Paul and Wyatt opened a mill in Birmingham which used their new rolling machine powered by a donkey. In 1743 a factory opened in Northampton with 50 spindles on each of five of Paul and Wyatt's machines. This operated until about 1764. A similar mill was built by Daniel Bourn in Leominster, but this burnt down.

Both Lewis Paul and Daniel Bourn patented carding machines in 1748. Based on two sets of rollers that travelled at different speeds, it was later used in the first cotton spinning mill. Lewis's invention was later developed and improved by Richard Arkwright in his water frame and Samuel Crompton in his spinning mule.

In 1764 in the village of Stanhill, Lancashire, James Hargreaves invented the spinning jenny, which he patented in 1770. It was the first practical spinning frame with multiple spindles. The jenny worked in a similar manner to the spinning wheel, by first clamping down on the fibres, then by drawing them out, followed by twisting. It was a simple, wooden framed machine that only cost about £6 for a 40-spindle model in 1792, and was used mainly by home spinners. The jenny produced a lightly twisted yarn only suitable for weft, not warp.

The spinning frame or water frame was developed by Richard Arkwright who, along with two partners, patented it in 1769. The design was partly based on a spinning machine built for Thomas High by clockmaker John Kay, who was hired by Arkwright. For each spindle the water frame used a series of four pairs of rollers, each operating at a successively higher rotating speed, to draw out the fibre, which was then twisted by the spindle. The roller spacing was slightly longer than the fibre length. Too close a spacing caused the fibres to break while too distant a spacing caused uneven thread. The top rollers were leather-covered and loading on the rollers was applied by a weight.

The weights kept the twist from backing up before the rollers. The bottom rollers were wood and metal, with fluting along the length. The water frame was able to produce a hard, medium count thread suitable for warp, finally allowing 100% cotton cloth to be made in Britain. A horse powered the first factory to use the spinning frame. Arkwright and his partners used water power at a factory in Cromford, Derbyshire in 1771, giving the invention its name.

Samuel Crompton's Spinning Mule was introduced in 1779. Mule implies a hybrid because it was a combination of the spinning jenny and the water frame, in which the spindles were placed on a carriage, which went through an operational sequence during which the rollers stopped while the carriage moved away from the drawing roller to finish drawing out the fibres as the spindles started rotating. Crompton's mule was able to produce finer thread than hand spinning and at a lower cost. Mule spun thread was of suitable strength to be used as warp, and finally allowed Britain to produce highly competitive yarn in large quantities.

Realising that the expiration of the Arkwright patent would greatly increase the supply of spun cotton and led to a shortage of weavers, Edmund Cartwright developed a vertical power loom which he patented in 1785. In 1776 he patented a two-man operated loom which was more conventional. Cartwright built two factories; the first burned down and the second was sabotaged by his workers. Cartwright's loom design had several flaws, the most serious being thread breakage. Samuel Horrocks patented a fairly successful loom in 1813. Horock's loom was improved by Richard Roberts in 1822 and these were produced in large numbers by Roberts, Hill & Co.

The demand for cotton presented an opportunity to planters in the Southern United States, who thought upland cotton would be a profitable crop if a better way could be found to remove the seed. Eli Whitney responded to the challenge by inventing the inexpensive cotton gin.

A man using a cotton gin could remove seed from as much upland cotton in one day as would previously, working at the rate of one pound of cotton per day, have taken a woman two months to process.

These advances were capitalised on by entrepreneurs, of whom the best known is Richard Arkwright. He is credited with a list of inventions, but these were actually developed by such people as Thomas Highs and John Kay; Arkwright nurtured the inventors, patented the ideas, financed the initiatives, and protected the machines.

He created the cotton mill which brought the production processes together in a factory, and he developed the use of power—first horse power and then water power—which made cotton manufacture a mechanised industry. Other inventors increased the efficiency of the individual steps of spinning (carding, twisting and spinning, and rolling) so that the supply of yarn increased greatly. Before long steam power was applied to drive textile machinery. Manchester acquired the nickname Cottonopolis during the early 19th century owing to its sprawl of textile factories. Although mechanization dramatically decreased the cost of cotton cloth, by the mid-19th century machine-woven cloth still could not equal the quality of hand-woven Indian cloth, in part due to the fineness of thread made possible by the type of cotton used in India, which allowed high thread counts.

However, the high productivity of British textile manufacturing allowed coarser grades of British cloth to undersell hand-spun and woven fabric in low-wage India, eventually destroying the industry.

Wool

The earliest European attempts at mechanized spinning were with wool; however, wool spinning proved more difficult to mechanize than cotton. Productivity improvement in wool spinning during the Industrial Revolution was significant but was far less than that of cotton.

Silk

Arguably the first highly mechanised factory was John Lombe's water-powered silk mill at Derby, operational by 1721. Lombe learned silk thread manufacturing by taking a job in Italy and acting as an industrial spy; however, because the Italian silk industry guarded its secrets closely, the state of the industry at that time is unknown. Although Lombe's factory was technically successful, the supply of raw silk from Italy was cut off to eliminate competition. In order to promote manufacturing the Crown paid for models of Lombe's machinery which were exhibited in the Tower of London.

Iron industry

UK iron production statistics

Bar iron was the commodity form of iron used as the raw material for making hardware goods such as nails, wire, hinges, horse shoes, wagon tires, chains, etc., as well as structural shapes.

A small amount of bar iron was converted into steel. Cast iron was used for pots, stoves and other items where its brittleness was tolerable. Most cast iron was refined and converted to bar iron, with substantial losses. Bar iron was also made by the bloomery process, which was the predominant iron smelting process until the late 18th century.

In the UK in 1720, there were 20,500 tons of cast iron produced with charcoal and 400 tons with coke. In 1750 charcoal iron production was 24,500 and coke iron was 2,500 tons. In 1788 the production of charcoal cast iron was 14,000 tons while coke iron production was 54,000 tons. In 1806 charcoal cast iron production was 7,800 tons and coke cast iron was 250,000 tons.

In 1750 the UK imported 31,200 tons of bar iron and either refined from cast iron or directly produced 18,800 tons of bar iron using charcoal and 100 tons using coke. In 1796 the UK was making 125,000 tons of bar iron with coke and 6,400 tons with charcoal; imports were 38,000 tons and exports were 24,600 tons. In 1806 the UK did not import bar iron but exported 31,500 tons.

Iron process innovations

A major change in the iron industries during the Industrial Revolution was the replacement of wood and other bio-fuels with coal. For a given amount of heat, mining coal required much less labour than cutting wood and converting it to charcoal, and coal was much more abundant than wood, supplies of which were becoming scarce before the enormous increase in iron production that took place in the late 18th century.

By 1750 coke had generally replaced charcoal in the smelting of copper and lead, and was in widespread use in glass production. In the smelting and refining of iron, coal and coke produced inferior iron to that made with charcoal because of the coal's sulfur content. Low sulfur coals were known, but they still contained harmful amounts. Conversion of coal to coke only slightly reduces the sulfur content. A minority of coals are coking.

Another factor limiting the iron industry before the Industrial Revolution was the scarcity of water power to power blast bellows. This limitation was overcome by the steam engine.

Use of coal in iron smelting started somewhat before the Industrial Revolution, based on innovations by Sir Clement Clerke and others from 1678, using coal reverberatory furnaces known as cupolas. These were operated by the flames playing on the ore and charcoal or coke mixture, reducing the oxide to metal. This has the advantage that impurities (such as sulphur ash) in the coal do not migrate into the metal. This technology was applied to lead from 1678 and to copper from 1687. It was also applied to iron foundry work in the 1690s, but in this case the reverberatory furnace was known as an air furnace. (The foundry cupola is a different, and later, innovation.)

By 1709 Abraham Darby made progress using coke to fuel his blast furnaces at Coalbrookdale. However, the coke pig iron he made was not suitable for making wrought iron and was used mostly for the production of cast iron goods, such as pots and kettles. He had the advantage over his rivals in that his pots, cast by his patented process, were thinner and cheaper than theirs.

Coke pig iron was hardly used to produce wrought iron until 1755–56, when Darby's son Abraham Darby II built furnaces at Horsehay and Ketley where low sulfur coal was available (and not far from Coalbrookdale). These new furnaces were equipped with water-powered bellows, the water being pumped by Newcomen steam engines. The Newcomen engines were not attached directly to the blowing cylinders because the engines alone could not produce a steady air blast. Abraham Darby III installed similar steam-pumped, water-powered blowing cylinders at the Dale Company when he took control in 1768. The Dale Company used several Newcomen engines to drain its mines and made parts for engines which it sold throughout the country.

Steam engines made the use of higher-pressure and volume blast practical; however, the leather used in bellows was expensive to replace. In 1757, iron master John Wilkinson patented a hydraulic powered blowing engine for blast furnaces. The blowing cylinder for blast furnaces was introduced in 1760 and the first blowing cylinder made of cast iron is believed to be the one used at Carrington in 1768 that was designed by John Smeaton.

Cast iron cylinders for use with a piston were difficult to manufacture; the cylinders had to be free of holes and had to be machined smooth and straight to remove any warping. James Watt had great difficulty trying to have a cylinder made for his first steam engine. In 1774 John Wilkinson, who built a cast iron blowing cylinder for his iron works, invented a precision boring machine for boring cylinders. After Wilkinson bored the first successful cylinder for a Boulton and Watt steam engine in 1776, he was given an exclusive contract for providing cylinders. After Watt developed a rotary steam engine in 1782, they were widely applied to blowing, hammering, rolling and slitting.

The solutions to the sulfur problem were the addition of sufficient limestone to the furnace to force sulfur into the slag and the use of low sulfur coal. Use of lime or limestone required higher furnace temperatures to form a free-flowing slag. The increased furnace temperature made possible by improved blowing also increased the capacity of blast furnaces and allowed for increased furnace height. In addition to lower cost and greater availability, coke had other important advantages over charcoal in that it was harder and made the column of materials (iron ore, fuel, slag) flowing down the blast furnace more porous and did not crush in the much taller furnaces of the late 19th century.

As cast iron became cheaper and widely available, it began being a structural material for bridges and buildings. A famous early example was the Iron Bridge built in 1778 with cast iron produced by Abraham Darby III. However, most cast iron was converted to wrought iron.

Europe relied on the bloomery for most of its wrought iron until the large scale production of cast iron. Conversion of cast iron was done in a finery forge, as it long had been. An improved refining process known as potting and stamping was developed, but this was superseded by Henry Cort's puddling process. Cort developed two significant iron manufacturing processes: rolling in 1783 and puddling in 1784. Puddling produced a structural grade iron at a relatively low cost.

Puddling was a means of decarburizing molten pig iron by slow oxidation in a reverberatory furnace by manually stirring it with a long rod. The decarburized iron, having a higher melting point than cast iron, was raked into globs by the puddler. When the glob was large enough, the puddler would remove it. Puddling was backbreaking and extremely hot work. Few puddlers lived to be 40. Because puddling was done in a reverberatory furnace, coal or coke could be used as fuel.

The puddling process continued to be used until the late 19th century when iron was being displaced by steel. Because puddling required human skill in sensing the iron globs, it was never successfully mechanised. Rolling was an important part of the puddling process because the grooved rollers expelled most of the molten slag and consolidated the mass of hot wrought iron. Rolling was 15 times faster at this than a trip hammer. A different use of rolling, which was done at lower temperatures than that for expelling slag, was in the production of iron sheets, and later structural shapes such as beams, angles and rails.

The puddling process was improved in 1818 by Baldwyn Rogers, who replaced some of the sand lining on the reverberatory furnace bottom with iron oxide. In 1838 John Hall patented the use of roasted tap cinder (iron silicate) for the furnace bottom, greatly reducing the loss of iron through increased slag caused by a sand lined bottom. The tap cinder also tied up some phosphorus, but this was not understood at the time. Hall's process also used iron scale or rust, which reacted with carbon in the molten iron. Hall's process, called *wet puddling*, reduced losses of iron with the slag from almost 50% to around 8%.

Puddling became widely used after 1800. Up to that time British iron manufacturers had used considerable amounts of iron imported from Sweden and Russia to supplement domestic supplies. Because of the increased British production, imports began to decline in 1785 and by the 1790s Britain eliminated imports and became a net exporter of bar iron.

Hot blast, patented by James Beaumont Neilson in 1828, was the most important development of the 19th century for saving energy in making pig iron. By using preheated combustion air, the amount of fuel to make a unit of pig iron was reduced at first by between one-third using coke or two-thirds using coal; however, the efficiency gains continued as the technology improved. Hot blast also raised the operating temperature of furnaces, increasing their capacity. Using less coal or coke meant introducing fewer impurities into the pig iron. This meant that lower quality coal or anthracite could be used in areas where coking coal was unavailable or too expensive; however, by the end of the 19th century transportation costs fell considerably.

Shortly before the Industrial Revolution an improvement was made in the production of steel, which was an expensive commodity and used only where iron would not do, such as for cutting edge tools and for springs. Benjamin Huntsman developed his crucible steel technique in the 1740s. The raw material for this was blister steel, made by the cementation process.

The supply of cheaper iron and steel aided a number of industries, such as those making nails, hinges, wire and other hardware items. The development of machine tools allowed better working of iron, causing it to be increasingly used in the rapidly growing machinery and engine industries.

Steam power

The development of the stationary steam engine was an important element of the Industrial Revolution; however, during the early period of the Industrial Revolution, most industrial power was supplied by water and wind. In Britain by 1800 an estimated 10,000 horsepower was being supplied by steam. By 1815 steam power had grown to 210,000 hp.

The first commercially successful industrial use of steam power was due to Thomas Savery in 1698. He constructed and patented in London a low-lift combined vacuum and pressure water pump, that generated about one horsepower (hp) and was used in numerous water works and in a few mines (hence its "brand name", *The Miner's Friend*). Savery's pump was economical in small horsepower ranges, but was prone to boiler explosions in larger sizes. Savery pumps continued to be produced until the late 18th century.

The first successful piston steam engine was introduced by Thomas Newcomen before 1712. A number of Newcomen engines were installed in Britain for draining hitherto unworkable deep mines, with the engine on the surface; these were large machines, requiring a significant amount of capital to build, and produced upwards of 3.5 kW (5 hp). They were also used to power municipal water supply pumps. They were extremely inefficient by modern standards, but when located where coal was cheap at pit heads, opened up a great expansion in coal mining by allowing mines to go deeper.

Despite their disadvantages, Newcomen engines were reliable and easy to maintain and continued to be used in the coalfields until the early decades of the 19th century. By 1729, when Newcomen died, his engines had spread (first) to Hungary in 1722, Germany, Austria, and Sweden. A total of 110 are known to have been built by 1733 when the joint patent expired, of which 14 were abroad. In the 1770s the engineer John Smeaton built some very large examples and introduced a number of improvements. A total of 1,454 engines had been built by 1800.

A fundamental change in working principles was brought about by Scotsman James Watt. With financial support from his business partner Englishman Matthew Boulton, he had succeeded by 1778 in perfecting his steam engine, which incorporated a series of radical improvements, notably the closing off of the upper part of the cylinder, thereby making the low-pressure steam drive the top of the piston instead of the atmosphere, use of a steam jacket and the celebrated separate steam condenser chamber. The separate condenser did away with the cooling water that had been injected directly into the cylinder, which cooled the cylinder and wasted steam. Likewise, the steam jacket kept steam from condensing in the cylinder, also improving efficiency. These improvements increased engine efficiency so that Boulton and Watt's engines used only 20–25% as much coal per horsepower-hour as Newcomen's. Boulton and Watt opened the Soho Foundry for the manufacture of such engines in 1795.

By 1783 the Watt steam engine had been fully developed into a double-acting rotative type, which meant that it could be used to directly drive the rotary machinery of a factory or mill. Both of Watt's basic engine types were commercially very successful, and by 1800, the firm Boulton & Watt had constructed 496 engines, with 164 driving reciprocating pumps, 24 serving blast furnaces, and 308 powering mill machinery; most of the engines generated from 3.5 to 7.5 kW (5 to 10 hp).

Until about 1800 the most common pattern of steam engine was the beam engine, built as an integral part of a stone or brick engine-house, but soon various patterns of self-contained rotative engines (readily removable, but not on wheels) were developed, such as the table engine. Around the start of the 19th century, at which time the Boulton and Watt patent expired, the Cornish engineer Richard Trevithick and the American Oliver Evans began to construct higher-pressure non-condensing steam engines, exhausting against the atmosphere. High pressure yielded an engine and boiler compact enough to be used on mobile road and rail locomotives and steam boats.

The development of machine tools, such as the engine lathe, planing, milling and shaping machines powered by these engines, enabled all the metal parts of the engines to be easily and accurately cut and in turn made it possible to build larger and more powerful engines.

Small industrial power requirements continued to be provided by animal and human muscle until widespread electrification in the early 20th century. These included crank-powered, treadle-powered and horse-powered workshop and light industrial machinery.

Machine tools

Pre-industrial machinery was built by various craftsmen—millwrights built water and windmills, carpenters made wooden framing, and smiths and turners made metal parts. Wooden components had the disadvantage of changing dimensions with temperature and humidity, and the various joints tended to rack (work loose) over time. As the Industrial Revolution progressed, machines with metal parts and frames became more common. Other important uses of metal parts were in firearms and threaded fasteners, such as machine screws, bolts and nuts. There was also the need for precision in making parts. Precision would allow better working machinery, interchangeability of parts and standardization of threaded fasteners.

The demand for metal parts led to the development of several machine tools. They have their origins in the tools developed in the 18th century by makers of clocks and watches and scientific instrument makers to enable them to batch-produce small mechanisms.

Before the advent of machine tools, metal was worked manually using the basic hand tools of hammers, files, scrapers, saws and chisels. Consequently, the use of metal machine parts was kept to a minimum. Hand methods of production were very laborious and costly and precision was difficult to achieve.

The first large precision machine tool was the cylinder boring machine invented by John Wilkinson in 1774. It was used for boring the large-diameter cylinders on early steam engines. Wilkinson's boring machine differed from earlier cantilevered machines used for boring cannon in that the cutting tool was mounted on a beam that ran through the cylinder being bored and was supported outside on both ends.

The planing machine, the milling machine and the shaping machine were developed in the early decades of the 19th century. Although the milling machine was invented at this time, it was not developed as a serious workshop tool until somewhat later in the 19th century.

Henry Maudslay, who trained a school of machine tool makers early in the 19th century, was a mechanic with superior ability who had been employed at the Royal Arsenal, Woolwich. He worked as an apprentice in the Royal Gun Foundry of Jan Verbruggen. In 1774 Jan Verbruggen had installed a horizontal boring machine in Woolwich which was the first industrial size lathe in the UK. Maudslay was hired away by Joseph Bramah for the production of high-security metal locks that required precision craftsmanship. Bramah patented a lathe that had similarities to the slide rest lathe.

Maudslay perfected the slide rest lathe, which could cut machine screws of different thread pitches by using changeable gears between the spindle and the lead screw. Before its invention screws could not be cut to any precision using various earlier lathe designs, some of which copied from a template. The slide rest lathe was called one of history's most important inventions. Although it was not entirely Maudslay's idea, he was the first person to build a functional lathe using a combination of known innovations of the lead screw, slide rest and change gears.

Maudslay left Bramah's employment and set up his own shop. He was engaged to build the machinery for making ships' pulley blocks for the Royal Navy in the Portsmouth Block Mills. These machines were all-metal and were the first machines for mass production and making components with a degree of interchangeability. The lessons Maudslay learned about the need for stability and precision he adapted to the development of machine tools, and in his workshops he trained a generation of men to build on his work, such as Richard Roberts, Joseph Clement and Joseph Whitworth.

James Fox of Derby had a healthy export trade in machine tools for the first third of the century, as did Matthew Murray of Leeds. Roberts was a maker of high-quality machine tools and a pioneer of the use of jigs and gauges for precision workshop measurement.

The effect of machine tools during the Industrial Revolution was not that great because other than firearms, threaded fasteners and a few other industries there were few mass-produced metal parts. The techniques to make mass-produced metal parts made with sufficient precision to be interchangeable is largely attributed to a program of the U.S. Department of War which perfected interchangeable parts for firearms in the early 19th century.

In the half century following the invention of the fundamental machine tools the machine industry became the largest industrial sector of the U.S. economy, by value added.

Chemicals

The large-scale production of chemicals was an important development during the Industrial Revolution. The first of these was the production of sulphuric acid by the lead chamber process invented by the Englishman John Roebuck (James Watt's first partner) in 1746. He was able to greatly increase the scale of the manufacture by replacing the relatively expensive glass vessels formerly used with larger, less expensive chambers made of riveted sheets of lead. Instead of making a small amount each time, he was able to make around 50 kilograms (100 pounds) in each of the chambers, at least a tenfold increase.

The production of an alkali on a large scale became an important goal as well, and Nicolas Leblanc succeeded in 1791 in introducing a method for the production of sodium carbonate. The Leblanc process was a reaction of sulfuric acid with sodium chloride to give sodium sulfate and hydrochloric acid. The sodium sulfate was heated with limestone (calcium carbonate) and coal to give a mixture of sodium carbonate and calcium sulfide. Adding water separated the soluble sodium carbonate from the calcium sulfide. The process produced a large amount of pollution (the hydrochloric acid was initially vented to the air, and calcium sulfide was a useless waste product).

Nonetheless, this synthetic soda ash proved economical compared to that from burning specific plants (barilla) or from kelp, which were the previously dominant sources of soda ash, and also to potash (potassium carbonate) produced from hardwood ashes.

These two chemicals were very important because they enabled the introduction of a host of other inventions, replacing many small-scale operations with more cost-effective and controllable processes.

Sodium carbonate had many uses in the glass, textile, soap, and paper industries. Early uses for sulfuric acid included pickling (removing rust from) iron and steel, and for bleaching cloth.

The development of bleaching powder (calcium hypochlorite) by Scottish chemist Charles Tennant in about 1800, based on the discoveries of French chemist Claude Louis Berthollet, revolutionised the bleaching processes in the textile industry by dramatically reducing the time required (from months to days) for the traditional process then in use, which required repeated exposure to the sun in bleach fields after soaking the textiles with alkali or sour milk. Tennant's factory at St Rollox, North Glasgow, became the largest chemical plant in the world.

After 1860 the focus on chemical innovation was in dyestuffs, and Germany took world leadership, building a strong chemical industry. Aspiring chemists flocked to German universities in the 1860–1914 era to learn the latest techniques. British scientists by contrast, lacked research universities and did not train advanced students; instead, the practice was to hire German-trained chemists.

Cement

In 1824 Joseph Aspdin, a British bricklayer turned builder, patented a chemical process for making portland cement which was an important advance in the building trades. This process involves sintering a mixture of clay and limestone to about 1,400 °C (2,552 °F), then grinding it into a fine powder which is then mixed with water, sand and gravel to produce concrete. Portland cement was used by the famous English engineer Marc Isambard Brunel several years later when constructing the Thames Tunnel. Cement was used on a large scale in the construction of the London sewerage system a generation later.

Gas lighting

Another major industry of the later Industrial Revolution was gas lighting. Though others made a similar innovation elsewhere, the large-scale introduction of this was the work of William Murdoch, an employee of Boulton & Watt, the Birmingham steam engine pioneers. The process consisted of the large-scale gasification of coal in furnaces, the purification of the gas (removal of sulphur, ammonia, and heavy hydrocarbons), and its storage and distribution. The first gas lighting utilities were established in London between 1812 and 1820. They soon became one of the major consumers of coal in the UK. Gas lighting affected social and industrial organisation because it allowed factories and stores to remain open longer than with tallow candles or oil. Its introduction allowed nightlife to flourish in cities and towns as interiors and streets could be lighted on a larger scale than before.

Glass making

Glass was made in ancient Greece and Rome. A new method of producing glass, known as the cylinder process, was developed in Europe during the early 19th century. In 1832 this process was used by the Chance Brothers to create sheet glass. They became the leading producers of window and plate glass. This advancement allowed for larger panes of glass to be created without interruption, thus freeing up the space planning in interiors as well as the fenestration of buildings. The Crystal Palace is the supreme example of the use of sheet glass in a new and innovative structure.

Paper machine

A machine for making a continuous sheet of paper on a loop of wire fabric was patented in 1798 by Nicholas Louis Robert who worked for Saint-Léger Didot family in France. The paper machine is known as a Fourdrinier after the financiers, brothers Sealy and Henry Fourdrinier, who were stationers in London. Although greatly improved and with many variations, the Fourdriner machine is the predominant means of paper production today.

The method of continuous production demonstrated by the paper machine influenced the development of continuous rolling of iron and later steel and other continuous production processes.

Agriculture

The British Agricultural Revolution is considered one of the causes of the Industrial Revolution because improved agricultural productivity freed up workers to work in other sectors of the economy. However, per-capita food supply in Europe was stagnant or declining and did not improve in some parts of Europe until the late 18th century.

Industrial technologies that affected farming included the seed drill, the Dutch plough, which contained iron parts, and the threshing machine.

The English lawyer Jethro Tull invented an improved seed drill in 1701. It was a mechanical seeder which distributed seeds evenly across a plot of land and planted them at the correct depth. This was important because the yield of seeds harvested to seeds planted at that time was around four or five. Tull's seed drill was very expensive and not very reliable and therefore did not have much of an effect. Good quality seed drills were not produced until the mid 18th century.

Joseph Foljambe's *Rotherham plough* of 1730 was the first commercially successful iron plough. The threshing machine, invented by the Scottish engineer Andrew Meikle in 1784, displaced hand threshing with a flail, a laborious job that took about one-quarter of agricultural labour. It took several decades to diffuse and was the final straw for many farm labourers, who faced near starvation, leading to the 1830 agricultural rebellion of the Swing Riots.

Machine tools and metalworking techniques developed during the Industrial Revolution eventually resulted in precision manufacturing techniques in the late 19th century for mass-producing agricultural equipment, such as reapers, binders and combine harvesters.

Mining

Coal mining in Britain, particularly in South Wales, started early. Before the steam engine, pits were often shallow bell pits following a seam of coal along the surface, which were abandoned as the coal was extracted.

In other cases, if the geology was favourable, the coal was mined by means of an adit or drift mine driven into the side of a hill. Shaft mining was done in some areas, but the limiting factor was the problem of removing water.

It could be done by hauling buckets of water up the shaft or to a sough (a tunnel driven into a hill to drain a mine). In either case, the water had to be discharged into a stream or ditch at a level where it could flow away by gravity.

The introduction of the steam pump by Thomas Savery in 1698 and the Newcomen steam engine in 1712 greatly facilitated the removal of water and enabled shafts to be made deeper, enabling more coal to be extracted.

These were developments that had begun before the Industrial Revolution, but the adoption of John Smeaton's improvements to the Newcomen engine followed by James Watt's more efficient steam engines from the 1770s reduced the fuel costs of engines, making mines more profitable. The Cornish engine, developed in the 1810s, was much more efficient than the Watt steam engine.

Coal mining was very dangerous owing to the presence of firedamp in many coal seams. Some degree of safety was provided by the safety lamp which was invented in 1816 by Sir Humphry Davy and independently by George Stephenson.

However, the lamps proved a false dawn because they became unsafe very quickly and provided a weak light. Firedamp explosions continued, often setting off coal dust explosions, so casualties grew during the entire 19th century. Conditions of work were very poor, with a high casualty rate from rock falls.

Transportation

At the beginning of the Industrial Revolution, inland transport was by navigable rivers and roads, with coastal vessels employed to move heavy goods by sea. Wagonways were used for conveying coal to rivers for further shipment, but canals had not yet been widely constructed.

Animals supplied all of the motive power on land, with sails providing the motive power on the sea. The first horse railways were introduced toward the end of the 18th century, with steam locomotives being introduced in the early decades of the 19th century. Improving sailing technologies boosted average sailing speed 50% between 1750 and 1830.

The Industrial Revolution improved Britain's transport infrastructure with a turnpike road network, a canal and waterway network, and a railway network. Raw materials and finished products could be moved more quickly and cheaply than before. Improved transportation also allowed new ideas to spread quickly.

Canals and improved waterways

Before and during the Industrial Revolution navigation on several British rivers was improved by removing obstructions, straightening curves, widening and deepening and building navigation locks. Britain had over 1,600 kilometres (1,000 mi) of navigable rivers and streams by 1750.

Canals and waterways allowed bulk materials to be economically transported long distances inland. This was because a horse could pull a barge with a load dozens of times larger than the load that could be drawn in a cart.

In the UK, canals began to be built in the late 18th century to link the major manufacturing centres across the country. Known for its huge commercial success, the Bridgewater Canal in North West England, which opened in 1761 and was mostly funded by The 3rd Duke of Bridgewater. From Worsley to the rapidly growing town of Manchester its construction cost £168,000 (£22,589,130 as of 2013), but its advantages over land and river transport meant that within a year of its opening in 1761, the price of coal in Manchester fell by about half. This success helped inspire a period of intense canal building, known as Canal Mania. New canals were hastily built in the aim of replicating the commercial success of the Bridgewater Canal, the most notable being the Leeds and Liverpool Canal and the Thames and Severn Canal which opened in 1774 and 1789 respectively.

By the 1820s a national network was in existence. Canal construction served as a model for the organisation and methods later used to construct the railways. They were eventually largely superseded as profitable commercial enterprises by the spread of the railways from the 1840s on. The last major canal to be built in the United Kingdom was the Manchester Ship Canal, which upon opening in 1894 was the largest ship canal in the world, and opened Manchester as a port. However it never achieved the commercial success its sponsors had hoped for and signalled canals as a dying mode of transport in an age dominated by railways, which were quicker and often cheaper.

Britain's canal network, together with its surviving mill buildings, is one of the most enduring features of the early Industrial Revolution to be seen in Britain.

Roads

France was known for having an excellent system of roads at the time of the Industrial Revolution; however, most of the roads on the European Continent and in the U.K. were in bad condition and dangerously rutted.

Much of the original British road system was poorly maintained by thousands of local parishes, but from the 1720s (and occasionally earlier) turnpike trusts were set up to charge tolls and maintain some roads. Increasing numbers of main roads were turnpiked from the 1750s to the extent that almost every main road in England and Wales was the responsibility of a turnpike trust. New engineered roads were built by John Metcalf, Thomas Telford and most notably John McAdam, with the first 'macadamised' stretch of road being Marsh Road at Ashton Gate, Bristol in 1816. The first macadamised road in the U.S. was the "Boonsborough Turnpike Road" between Hagerstown and Boonsboro, Maryland in 1823.

The major turnpikes radiated from London and were the means by which the Royal Mail was able to reach the rest of the country. Heavy goods transport on these roads was by means of slow, broad wheeled, carts hauled by teams of horses. Lighter goods were conveyed by smaller carts or by teams of pack horse. Stagecoaches carried the rich, and the less wealthy could pay to ride on carriers carts.

Productivity of road transport increased greatly during the Industrial Revolution and the cost of travel fell dramatically. Between 1690 and 1840 productivity almost tripled for long-distance carrying and increased four-fold in stage coaching.

Railways

Reducing friction was one of the major reasons for the success of railroads compared to wagons. This was demonstrated on an iron plate covered wooden tramway in 1805 at Croydon, England.

"A good horse on an ordinary turnpike road can draw two thousand pounds, or one ton. A party of gentlemen were invited to witness the experiment, that the superiority of the new road might be established by ocular demonstration. Twelve wagons were loaded with stones, till each wagon weighed three tons, and the wagons were fastened together. A horse was then attached, which drew the wagons with ease, six miles [10 km] in two hours, having stopped four times, in order to show he had the power of starting, as well as drawing his great load."

Railways were made practical by the widespread introduction of inexpensive puddled iron after 1800, the rolling mill for making rails, and the development of the high-pressure steam engine also around 1800.

Wagonways for moving coal in the mining areas had started in the 17th century and were often associated with canal or river systems for the further movement of coal. These were all horse drawn or relied on gravity, with a stationary steam engine to haul the wagons back to the top of the incline. The first applications of the steam locomotive were on wagon or plate ways (as they were then often called from the cast-iron plates used). Horse-drawn public railways did not begin until the early years of the 19th century when improvements to pig and wrought iron production were lowering costs. Steam locomotives began being built after the introduction of high-pressure steam engines after the expiration of the Boulton and Watt patent in 1800. High-pressure engines exhausted used steam to the atmosphere, doing away with the condenser and cooling water. They were also much lighter weight and smaller in size for a given horsepower than the stationary condensing engines. A few of these early locomotives were used in mines. Steam-hauled public railways began with the Stockton and Darlington Railway in 1825.

The rapid introduction of railways followed the 1829 Rainhill Trials, which demonstrated Robert Stephenson's successful locomotive design and the 1828 development of hot blast, which dramatically reduced the fuel consumption of making iron and increased the capacity of the blast furnace. On 15 September 1830, the Liverpool and Manchester Railway, the first inter-city railway in the world, was opened, and was attended by Prime Minister, the Duke of Wellington. The railway was engineered by Joseph Locke and George Stephenson, linked the rapidly expanding industrial town of Manchester with the port town of Liverpool. The opening was marred by problems, due to the primitive nature of the technology being employed, however problems were gradually ironed out and the railway became highly successful, transporting passengers and freight. The success of the inter-city railway, particularly in the transport of freight and commodities, led to Railway Mania. Construction of major railways connecting the larger cities and towns began in the 1830s but only gained momentum at the very end of the first Industrial Revolution. After many of the workers had completed the railways, they did not return to their rural lifestyles but instead remained in the cities, providing additional workers for the factories.

Other developments

Other developments included more efficient water wheels, based on experiments conducted by the British engineer John Smeaton, the beginnings of a machine industry and the rediscovery of concrete (based on hydraulic lime mortar) by John Smeaton, which had been lost for 1,300 years.

Social effects

Factory system

Prior to the Industrial Revolution, most of the workforce was employed in agriculture, either as self-employed farmers as landowners or tenants, or as landless agricultural labourers. It was common for families in various parts of the world to spin yarn, weave cloth and make their own clothing. Households also spun and wove for market production. At the beginning of the Industrial Revolution India, China and regions of Iraq and elsewhere in Asia and the Middle East produced most of the world's cotton cloth while Europeans produced wool and linen goods.

In Britain by the 16th century the putting-out system, by which farmers and townspeople produced goods for market in their homes, often described as *cottage industry*, was being practiced. Typical putting out system goods included spinning and weaving. Merchant capitalists typically provided the raw materials, paid workers by the piece, and were responsible for the sale of the goods. Embezzlement of supplies by workers and poor quality were common problems. The logistical effort in procuring and distributing raw materials and picking up finished goods were also limitations of the putting out system.

Some early spinning and weaving machinery, such as a 40 spindle jenny for about six pounds in 1792, was affordable for cottagers. Later machinery such as spinning frames, spinning mules and power looms were expensive (especially if water powered), giving rise to capitalist ownership of factories.

The majority of textile factory workers during the Industrial Revolution were unmarried women and children, including many orphans. They typically worked for 12 to 14 hours per day with only Sundays off. It was common for women take factory jobs seasonally during slack periods of farm work. Lack of adequate transportation, long hours and poor pay made it difficult to recruit and maintain workers. Many workers, such as displaced farmers and agricultural workers, who had nothing but their labour to sell, became factory workers out of necessity. (See: British Agricultural Revolution, Threshing machine)

The change in the social relationship of the factory worker compared to farmers and cottagers was viewed unfavourably by Karl Marx; however, he recognized the increase in productivity made possible by technology.

Standards of living

Some economists, such as Robert E. Lucas, Jr., say that the real effect of the Industrial Revolution was that "for the first time in history, the living standards of the masses of ordinary people have begun to undergo sustained growth ... Nothing remotely like this economic behaviour is mentioned by the classical economists, even as a theoretical possibility." Others, however, argue that while growth of the economy's overall productive powers was unprecedented during the Industrial Revolution, living standards for the majority of the population did not grow meaningfully until the late 19th and 20th centuries, and that in many ways workers' living standards declined under early capitalism: for instance, studies have shown that real wages in Britain only increased 15% between the 1780s and 1850s, and that life expectancy in Britain did not begin to dramatically increase until the 1870s. Similarly, the average height of the population declined during the Industrial Revolution, implying that their nutritional status was also decreasing. Real wages were not keeping up with the price of food.

During the Industrial Revolution, the life expectancy of children increased dramatically. The percentage of the children born in London who died before the age of five decreased from 74.5% in 1730–1749 to 31.8% in 1810–1829.

The effects on living conditions of the industrial revolution have been very controversial, and were hotly debated by economic and social historians from the 1950s to the 1980s. A series of 1950s essays by Henry Phelps Brown and Sheila V. Hopkins later set the academic consensus that the bulk of the population, that was at the bottom of the social ladder, suffered severe reductions in their living standards. During 1813–1913, there was a significant increase in worker wages.

Food and nutrition

Chronic hunger and malnutrition were the norm for the majority of the population of the world including Britain and France, until the late 19th century. Until about 1750, in large part due to malnutrition, life expectancy in France was about 35 years and about 40 years in Britain. The United States population of the time was adequately fed, much taller on average and had life expectancy of 45–50 years although U.S. life expectancy declined by a few years by the mid 19th century. Food consumption per capita also declined during an episode known as the Antebellum Puzzle.

Food supply in Great Britain was adversely affected by the Corn Laws (1815–1846). The Corn Laws, which imposed tariffs on imported grain, were enacted to keep prices high in order to benefit domestic producers. The Corn Laws were repealed in the early years of the Great Irish Famine.

The initial technologies of the Industrial Revolution, such as mechanized textiles, iron and coal, did little, if anything, to lower food prices. In Britain and the Netherlands, food supply increased before the Industrial Revolution due to better agricultural practices; however, population grew too, as noted by Thomas Malthus. This condition is called the Malthusian trap, and it finally started to be overcome by transportation improvements, such as canals, improved roads and steamships. Railroads and steamships were introduced near the end of the Industrial Revolution.

Housing

The rapid population growth in the 19th century included the new industrial and manufacturing cities, as well as service centers such as Edinburgh and London. The critical factor was financing, which was handled by building societies that dealt directly with large contracting firms. Private renting from housing landlords was the dominant tenure. P. Kemp says this was usually of advantage to tenants. People moved in so rapidly there was not enough capital to build adequate housing for everyone, so low-income newcomers squeezed into increasingly overcrowded slums. Clean water, sanitation, and public health facilities were inadequate; the death rate was high, especially infant mortality, and tuberculosis among young adults. Cholera from polluted water and typhoid were endemic. Unlike rural areas, there were no famines such as the one that devastated Ireland in the 1840s.

A large exposé literature grew up condemning the unhealthy conditions. By far the most famous publication was by one of the founders of the Socialist movement, *The Condition of the*

Working Class in England in 1844 Friedrich Engels described backstreet sections of Manchester and other mill towns, where people lived in crude shanties and shacks, some not completely enclosed, some with dirt floors. These shanty towns had narrow walkways between irregularly shaped lots and dwellings. There were no sanitary facilities. Population density was extremely high. However, not everyone lived in such poor conditions. The Industrial Revolution also created a middle class of businessmen, clerks, foremen and engineers who lived in much better conditions.

Conditions improved over the course of the 19th century due to new public health acts regulating things such as sewage, hygiene and home construction. In the introduction of his 1892 edition, Engels notes that most of the conditions he wrote about in 1844 had been greatly improved. For example, the Public Health Act 1875 led to the more sanitary byelaw terraced house.

Sanitation

In *The Condition of the Working Class in England* in 1844 Friedrich Engels described how untreated sewage created awful odours and turned the rivers green in industrial cities.

In 1854 John Snow traced a cholera outbreak in Soho in London to faecal contamination of a public water well by a home cesspit. Snow's findings that cholera could be spread by contaminated water took some years to be accepted, but his work led to fundamental changes in the design of public water and waste systems.

Water supply

Pre-industrial water supply relied on gravity systems and pumping of water was done by water wheels. Pipes were typically made of wood. Steam powered pumps and iron pipes allowed the widespread piping of water to horse watering troughs and households.

Literacy and industrialization

Modern industrialization began in England and Scotland in the 18th century, where there were relatively high levels of literacy among farmers, especially in Scotland. This permitted the recruitment of literate craftsman, skilled workers, foremen and managers who supervised the emerging textile factories and coal mines. Much of a labor was unskilled, and especially in textile mills children as young as eight proved useful in handling chores and adding to the family income. Indeed, children were taken out of school to work alongside their parents in the factories. However, by the mid-nineteenth century, unskilled labor forces were common in Western Europe, and British industry moved upscale, needing many more engineers and skilled workers who could handle technical instructions and handle complex situations. Literacy was essential to be hired. A senior government official told Parliament in 1870:

- Upon the speedy provision of elementary education depends are industrial prosperity. It is of no use trying to give technical teaching to our citizens without elementary education; uneducated labourers—and many of our labourers are utterly

> uneducated—are, for the most part, unskilled labourers, and if we leave our work–folk any longer unskilled, notwithstanding their strong sinews and determined energy, they will become overmatched in the competition of the world.

The invention of the paper machine and the application of steam power to the industrial processes of printing supported a massive expansion of newspaper and pamphlet publishing, which contributed to rising literacy and demands for mass political participation.

Clothing and consumer goods

Consumers benefited from falling prices for clothing and household articles such as cast iron cooking utensils, and in the following decades, stoves for cooking and space heating. Coffee, tea, sugar, tobacco and chocolate became affordable to many in Europe. The consumer revolution in England from the early 1600s to roughly 1750 had seen a marked increase in the consumption and variety of luxury goods and products by individuals from different economic and social backgrounds. With improvements in transport and manufacturing technology, opportunities for buying and selling became faster and more efficient than previous. The expanding textile trade in the north of England meant the three-piece suit became affordable to the masses. Founded by Josiah Wedgwood in 1759, Wedgwood fine china and porcelain tableware was starting to become a common feature on dining tables. Rising prosperity and social mobility in the 18th century increased the number of people with disposable income for consumption, and the marketing of goods (of which Wedgwood was a pioneer) for individuals as opposed to items for the household started to appear, and the new status of goods as status symbols related to changes in fashion and desired for aesthetic appeal.

With the rapid growth of towns and cities, shopping became an important part of everyday life. Window shopping and the purchase of goods became a cultural activity in its own right, and many exclusive shops were opened in elegant urban districts: in the Strand and Piccadilly in London, for example, and in spa towns such as Bath and Harrogate. Prosperity and expansion in manufacturing industries such as pottery and metalwares increased consumer choice dramatically. Where once labourers ate from metal platters with wooden implements, ordinary workers now dined on Wedgwood porcelain. Consumers came to demand an array of new household goods and furnishings: metal knives and forks, for example, as well as rugs, carpets, mirrors, cooking ranges, pots, pans, watches, clocks and a dizzying array of furniture. The age of mass consumption had arrived.

- *— "Georgian Britain, The rise of consumerism", Dr Matthew White, British Library.*

Increased literacy rates, industrialisation, and the invention of railway created a new market for cheap popular literature for the masses and the ability for it to be circulated on a large scale. Penny dreadfuls were created in the 1830s to meet this demand. *The Guardian* described penny dreadfuls as "Britain's first taste of mass-produced popular culture for the young", and "the Victorian equivalent of video games". By the 1860s and 1870s more than one million boys' periodicals were sold per week. Labelled an "authorpreneur" by the *Paris Review*, Charles Dickens used innovations from the revolution to sell his books, such as the powerful new printing presses, enhanced advertising revenues and the expansion of railroads. His first novel, *The Pickwick Papers* (1836), became a publishing phenomenon, with its unprecedented success sparking numerous spin-offs and merchandise ranging from *Pickwick* cigars, playing cards, china figurines, Sam Weller puzzles, Weller boot polish and joke books. Nicholas Dames in *The Atlantic* writes, "Literature" is not a big enough category for *Pickwick*. It defined its own, a new one that we have learned to call "entertainment."

In 1861, Welsh entrepreneur Pryce Pryce-Jones formed the first mail order business, an idea which would change the nature of retail. Selling Welsh flannel, he created mail order catalogues, with customers able to order by mail for the first time—this following the Uniform Penny Post in 1840 and the invention of the postage stamp (Penny Black) where there was a charge of one penny for carriage and delivery between any two places in the United Kingdom irrespective of distance—and the goods were delivered throughout the UK via the newly created railway system. As the railway network expanded overseas, so did his business.

Population increase

The Industrial Revolution was the first period in history during which there was a simultaneous increase in both population and per capita income. According to Robert Hughes in *The Fatal Shore*, the population of England and Wales, which had remained steady at six million from 1700 to 1740, rose dramatically after 1740. The population of England had more than doubled from 8.3 million in 1801 to 16.8 million in 1850 and, by 1901, had nearly doubled again to 30.5 million. Improved conditions led to the population of Britain increasing from 10 million to 40 million in the 1800s. Europe's population increased from about 100 million in 1700 to 400 million by 1900.

Urbanization

The growth of modern industry since the late 18th century led to massive urbanisation and the rise of new great cities, first in Europe and then in other regions, as new opportunities brought huge numbers of migrants from rural communities into urban areas. In 1800, only 3% of the world's population lived in cities, compared to nearly 50% today (the beginning of the 21st century). Manchester had a population of 10,000 in 1717, but by 1911 it had burgeoned to 2.3 million.

Effect on women and family life

Women's historians have debated the effect of the Industrial Revolution and capitalism generally on the status of women. Taking a pessimistic side, Alice Clark argued that when capitalism arrived in 17th-century England, it lowered the status of women as they lost much of their economic importance. Clark argues that in 16th-century England, women were engaged in many aspects of industry and agriculture. The home was a central unit of production and women played a vital role in running farms, and in some trades and landed estates. Their useful economic roles gave them a sort of equality with their husbands. However, Clark argues, as capitalism expanded in the 17th century, there was more and more division of labour with the husband taking paid labour jobs outside the home, and the wife reduced to unpaid household work. Middle- and upper-class women were confined to an idle domestic existence, supervising servants; lower-class women were forced to take poorly paid jobs. Capitalism, therefore, had a negative effect on powerful women. In a more positive interpretation, Ivy Pinchbeck argues that capitalism created the conditions for women's emancipation. Tilly and Scott have emphasised the continuity in the status of women, finding three stages in English history. In the pre-industrial era, production was mostly for home use and women produce much of the needs of the households. The second stage was the "family wage economy" of early industrialisation; the entire family depended on the collective wages of its members, including husband, wife and older children. The third or modern stage is the "family consumer economy," in which the family is the site of consumption, and women are employed in large numbers in retail and clerical jobs to support rising standards of consumption. Ideas of thrift and hard work characterized middle-class families as the Industrial Revolution swept Europe. These values were displayed in Samuel Smiles' book *Self-Help*, in which he states that the misery of the poorer classes was "voluntary and self-imposed – the results of idleness, thriftlessness, intemperance, and misconduct."

Labour conditions

Social structure and working conditions

In terms of social structure, the Industrial Revolution witnessed the triumph of a middle class of industrialists and businessmen over a landed class of nobility and gentry. Ordinary working people found increased opportunities for employment in the new mills and factories, but these were often under strict working conditions with long hours of labour dominated by a pace set by machines. As late as the year 1900, most industrial workers in the United States still worked a 10-hour day (12 hours in the steel industry), yet earned from 20% to 40% less than the minimum deemed necessary for a decent life; however, most workers in textiles, which was by far the leading industry in terms of employment, were women and children. For workers of the labouring classes, industrial life "was a stony desert, which they had to make habitable by their own efforts." Also, harsh working conditions were prevalent long before the Industrial Revolution took place. Pre-industrial society was very static and often cruel – child labour, dirty living conditions, and long working hours were just as prevalent before the Industrial Revolution.

Factories and urbanisation

Industrialisation led to the creation of the factory. The factory system contributed to the growth of urban areas, as large numbers of workers migrated into the cities in search of work in the factories. Nowhere was this better illustrated than the mills and associated industries of Manchester, nicknamed "Cottonopolis", and the world's first industrial city. Manchester experienced a six-times increase in its population between 1771 and 1831. Bradford grew by 50% every ten years between 1811 and 1851 and by 1851 only 50% of the population of Bradford was actually born there. In addition, between 1815 and 1939, 20 percent of Europe's population left home, pushed by poverty, a rapidly growing population, and the displacement of peasant farming and artisan manufacturing. They were pulled abroad by the enormous demand for labour overseas, the ready availability of land, and cheap transportation. Still, many did not find a satisfactory life in their new homes, leading 7 million of them to return to Europe. This mass migration had large demographic effects: in 1800, less than one percent of the world population consisted of overseas Europeans and their descendants; by 1930, they represented 11 percent. The Americas felt the brunt of this huge emigration, largely concentrated in the United States.

For much of the 19th century, production was done in small mills, which were typically water-powered and built to serve local needs. Later, each factory would have its own steam engine and a chimney to give an efficient draft through its boiler.

In other industries, the transition to factory production was not so divisive. Some industrialists themselves tried to improve factory and living conditions for their workers. One of the earliest such reformers was Robert Owen, known for his pioneering efforts in improving conditions for workers at the New Lanark mills, and often regarded as one of the key thinkers of the early socialist movement.

By 1746 an integrated brass mill was working at Warmley near Bristol. Raw material went in at one end, was smelted into brass and was turned into pans, pins, wire, and other goods. Housing was provided for workers on site. Josiah Wedgwood and Matthew Boulton (whose Soho Manufactory was completed in 1766) were other prominent early industrialists, who employed the factory system.

Child labour

The Industrial Revolution led to a population increase but the chances of surviving childhood did not improve throughout the Industrial Revolution, although *infant* mortality rates were reduced markedly. There was still limited opportunity for education and children were expected to work. Employers could pay a child less than an adult even though their productivity was comparable; there was no need for strength to operate an industrial machine, and since the industrial system was completely new, there were no experienced adult labourers. This made child labour the labour of choice for manufacturing in the early phases of the Industrial Revolution between the 18th and 19th centuries. In England and Scotland in 1788, two-thirds of the workers in 143 water-powered cotton mills were described as children.

Child labour existed before the Industrial Revolution but with the increase in population and education it became more visible. Many children were forced to work in relatively bad conditions for much lower pay than their elders, 10–20% of an adult male's wage.

Reports were written detailing some of the abuses, particularly in the coal mines and textile factories, and these helped to popularise the children's plight. The public outcry, especially among the upper and middle classes, helped stir change in the young workers' welfare.

Politicians and the government tried to limit child labour by law but factory owners resisted; some felt that they were aiding the poor by giving their children money to buy food to avoid starvation, and others simply welcomed the cheap labour. In 1833 and 1844, the first general laws against child labour, the Factory Acts, were passed in Britain: Children younger than nine were not allowed to work, children were not permitted to work at night, and the work day of youth under the age of 18 was limited to twelve hours. Factory inspectors supervised the execution of the law, however, their scarcity made enforcement difficult. About ten years later, the employment of children and women in mining was forbidden. Although laws such as these decreased the number of child labourers, child labour remained significantly present in Europe and the United States until the 20th century.

Organisation of labour

The Industrial Revolution concentrated labour into mills, factories and mines, thus facilitating the organisation of *combinations* or trade unions to help advance the interests of working people. The power of a union could demand better terms by withdrawing all labour and causing a consequent cessation of production. Employers had to decide between giving in to the union demands at a cost to themselves or suffering the cost of the lost production. Skilled workers were hard to replace, and these were the first groups to successfully advance their conditions through this kind of bargaining.

The main method the unions used to effect change was strike action. Many strikes were painful events for both sides, the unions and the management. In Britain, the Combination Act 1799 forbade workers to form any kind of trade union until its repeal in 1824. Even after this, unions were still severely restricted. One British newspaper in 1834 described unions as "the most dangerous institutions that were ever permitted to take root, under shelter of law, in any country..."

In 1832, the Reform Act extended the vote in Britain but did not grant universal suffrage. That year six men from Tolpuddle in Dorset founded the Friendly Society of Agricultural Labourers to protest against the gradual lowering of wages in the 1830s. They refused to work for less than ten shillings a week, although by this time wages had been reduced to seven shillings a week and were due to be further reduced to six.

In 1834 James Frampton, a local landowner, wrote to the Prime Minister, Lord Melbourne, to complain about the union, invoking an obscure law from 1797 prohibiting people from swearing oaths to each other, which the members of the Friendly Society had done. James Brine, James Hammett, George Loveless, George's brother James Loveless, George's brother in-law Thomas Standfield, and Thomas's son John Standfield were arrested, found guilty, and transported to Australia.

They became known as the Tolpuddle Martyrs. In the 1830s and 1840s, the Chartist movement was the first large-scale organised working class political movement which campaigned for political equality and social justice. Its *Charter* of reforms received over three million signatures but was rejected by Parliament without consideration.

Working people also formed friendly societies and co-operative societies as mutual support groups against times of economic hardship. Enlightened industrialists, such as Robert Owen also supported these organisations to improve the conditions of the working class.

Unions slowly overcame the legal restrictions on the right to strike. In 1842, a general strike involving cotton workers and colliers was organised through the Chartist movement which stopped production across Great Britain.

Eventually, effective political organisation for working people was achieved through the trades unions who, after the extensions of the franchise in 1867 and 1885, began to support socialist political parties that later merged to become the British Labour Party.

Luddites

The rapid industrialisation of the English economy cost many craft workers their jobs. The movement started first with lace and hosiery workers near Nottingham and spread to other areas of the textile industry owing to early industrialisation. Many weavers also found themselves suddenly unemployed since they could no longer compete with machines which only required relatively limited (and unskilled) labour to produce more cloth than a single weaver.

Many such unemployed workers, weavers, and others, turned their animosity towards the machines that had taken their jobs and began destroying factories and machinery. These attackers became known as Luddites, supposedly followers of Ned Ludd, a folklore figure.

The first attacks of the Luddite movement began in 1811. The Luddites rapidly gained popularity, and the British government took drastic measures, using the militia or army to protect industry. Those rioters who were caught were tried and hanged, or transported for life.

Unrest continued in other sectors as they industrialised, such as with agricultural labourers in the 1830s when large parts of southern Britain were affected by the Captain Swing disturbances. Threshing machines were a particular target, and hayrick burning was a popular activity. However, the riots led to the first formation of trade unions, and further pressure for reform.

Shift in production's center of gravity

The traditional centers of hand textile production such as India, parts of the Middle East and later China could not withstand the competition from machine-made textiles, which over a period of decades destroyed the hand made textile industries and left millions of people without work, many of whom starved.

The Industrial Revolution also generated an enormous and unprecedented economic division in the world, as measured by the share of manufacturing output.

Effect on cotton production and expansion of slavery

Cheap cotton textiles increased the demand for raw cotton; previously, it had primarily been consumed in subtropical regions where it was grown, with little raw cotton available for export. Consequently, prices of raw cotton rose. Some cotton had been grown in the West Indies, particularly in Hispaniola, but Haitian cotton production was halted by the Haitian Revolution in 1791. The invention of the cotton gin in 1792 allowed Georgia green seeded cotton to be profitable, leading to the widespread growth of cotton plantations in the United

States and Brazil. In 1791 world cotton production was estimated to be 490,000,000 pounds with U.S. production accounting to 2,000,000 pounds. By 1800, U.S. production was 35,000,000 pounds, of which 17,790,000 were exported. In 1945 the U.S. produced seven-eights of the 1,169,600,000 pounds of world production.

The Americas, particularly the U.S., had labour shortages and high priced labour, which made slavery attractive. America's cotton plantations were highly efficient and profitable, and able to keep up with demand. The U.S. Civil War created a "cotton famine" that led to increased production in other areas of the world, including new colonies in Africa.

Effect on environment

The origins of the environmental movement lay in the response to increasing levels of smoke pollution in the atmosphere during the Industrial Revolution. The emergence of great factories and the concomitant immense growth in coal consumption gave rise to an unprecedented level of air pollution in industrial centers; after 1900 the large volume of industrial chemical discharges added to the growing load of untreated human waste.

The first large-scale, modern environmental laws came in the form of Britain's Alkali Acts, passed in 1863, to regulate the deleterious air pollution (gaseous hydrochloric acid) given off by the Leblanc process, used to produce soda ash. An Alkali inspector and four sub-inspectors were appointed to curb this pollution. The responsibilities of the inspectorate were gradually expanded, culminating in the Alkali Order 1958 which placed all major heavy industries that emitted smoke, grit, dust and fumes under supervision.

The manufactured gas industry began in British cities in 1812–1820. The technique used produced highly toxic effluent that was dumped into sewers and rivers. The gas companies were repeatedly sued in nuisance lawsuits. They usually lost and modified the worst practices. The City of London repeatedly indicted gas companies in the 1820s for polluting the Thames and poisoning its fish. Finally, Parliament wrote company charters to regulate toxicity. The industry reached the US around 1850 causing pollution and lawsuits.

In industrial cities local experts and reformers, especially after 1890, took the lead in identifying environmental degradation and pollution, and initiating grass-roots movements to demand and achieve reforms. Typically the highest priority went to water and air pollution.

The Coal Smoke Abatement Society was formed in Britain in 1898 making it one of the oldest environmental NGOs. It was founded by artist Sir William Blake Richmond, frustrated with the pall cast by coal smoke.

Although there were earlier pieces of legislation, the Public Health Act 1875 required all furnaces and fireplaces to consume their own smoke. It also provided for sanctions against factories that emitted large amounts of black smoke. The provisions of this law were extended in 1926 with the Smoke Abatement Act to include other emissions, such as soot, ash, and gritty particles and to empower local authorities to impose their own regulations.

Nations and nationalism

In his 1983 book *Nations and Nationalism*, philosopher Ernest Gellner argues that the industrial revolution and economic modernization spurred the creation of nations.

Industrialisation beyond Great Britain

Continental Europe

The Industrial Revolution in Continental Europe came later than in Great Britain. It started in Belgium and France, then spread to the German states by the middle of the 19th century. In many industries, this involved the application of technology developed in Britain in new places. Typically the technology was purchased from Britain or British engineers and entrepreneurs moved abroad in search of new opportunities. By 1809, part of the Ruhr Valley in Westphalia was called 'Miniature England' because of its similarities to the industrial areas of Britain. Most European governments provided state funding to the new industries. In some cases (such as iron), the different availability of resources locally meant that only some aspects of the British technology were adopted.

Austria-Hungary

The Habsburg realms which became Austria-Hungary in 1867 included 23 million inhabitants in 1800, growing to 36 million by 1870. Nationally the per capita rate of industrial growth averaged about 3% between 1818 and 1870. However, there were strong regional differences. The railway system was built in the 1850-1873 period. Before they arrived transportation was very slow and expensive. In the Alpine and Bohemian (modern-day Czech Republic) regions, proto-industrialization began by 1750 and became the center of the first phases of the industrial revolution after 1800. The textile industry was the main factor, utilizing mechanization, steam engines, and the factory system. In the Czech lands, the "first mechanical loom followed in Varnsdorf in 1801," with the first steam engines appearing in Bohemia and Moravia just a few years later. The textile production flourished particularly in Prague and Brno (German: Brünn), which was considered the 'Moravian Manchester'. The Czech lands, especially Bohemia, became the center of industrialization due to its natural and human resources. The iron industry had developed in the Alpine regions after 1750, with smaller centers in Bohemia and Moravia. Hungary—the eastern half of the Dual Monarchy, was heavily rural with little industry before 1870.

In 1791 Prague organized the first World's Fair/List of world's fairs, Bohemia (modern-day Czech Republic). The first industrial exhibition was on the occasion of the coronation of Leopold II as a king of Bohemia, which took place in Clementinum, and therefore celebrated the considerable sophistication of manufacturing methods in the Czech lands during that time period.

Technological change accelerated industrialization and urbanization. The GNP per capita grew roughly 1.76% per year from 1870 to 1913. That level of growth compared very favorably to that of other European nations such as Britain

(1%), France (1.06%), and Germany (1.51%). However, in a comparison with Germany and Britain: the Austro-Hungarian economy as a whole still lagged considerably, as sustained modernization had begun much later.

Belgium

Belgium was the second country in which the Industrial Revolution took place and the first in continental Europe: Wallonia (French-speaking southern Belgium) took the lead. Starting in the middle of the 1820s, and especially after Belgium became an independent nation in 1830, numerous works comprising coke blast furnaces as well as puddling and rolling mills were built in the coal mining areas around Liège and Charleroi. The leader was a transplanted Englishman John Cockerill. His factories at Seraing integrated all stages of production, from engineering to the supply of raw materials, as early as 1825.

Wallonia exemplified the radical evolution of industrial expansion. Thanks to coal (the French word "houille" was coined in Wallonia), the region geared up to become the 2nd industrial power in the world after Britain. But it is also pointed out by many researchers, with its *Sillon industriel*, 'Especially in the Haine, Sambre and Meuse valleys, between the Borinage and Liège...there was a huge industrial development based on coal-mining and iron-making...'. Philippe Raxhon wrote about the period after 1830: "It was not propaganda but a reality the Walloon regions were becoming the second industrial power all over the world after Britain." "The sole industrial centre outside the collieries and blast furnaces of Walloon was the old cloth-making town of Ghent."

Professor Michel De Coster stated: "The historians and the economists say that Belgium was the second industrial power of the world, in proportion to its population and its territory [...] But this rank is the one of Wallonia where the coal-mines, the blast furnaces, the iron and zinc factories, the wool industry, the glass industry, the weapons industry... were concentrated." Many of the 19th century coal mines in Wallonia are now protected as World Heritage sites

Wallonia was also the birthplace of a strong Socialist party and strong trade-unions in a particular sociological landscape. At the left, the *Sillon industriel*, which runs from Mons in the west, to Verviers in the east (except part of North Flanders, in another period of the industrial revolution, after 1920). Even if Belgium is the second industrial country after Britain, the effect of the industrial revolution there was very different. In 'Breaking stereotypes', Muriel Neven and Isabelle Devious say:

The industrial revolution changed a mainly rural society into an urban one, but with a strong contrast between northern and southern Belgium. During the Middle Ages and the Early Modern Period, Flanders was characterised by the presence of large urban centres [...] at the beginning of the nineteenth century this region (Flanders), with an urbanisation degree of more than 30 per cent, remained one of the most urbanised in the world. By comparison, this proportion reached only 17 per cent in Wallonia, barely 10 per cent in most West European countries, 16 per cent in France and 25 per cent in Britain. Nineteenth century industrialisation did not affect the traditional urban infrastructure, except in Ghent....Also, in Wallonia the traditional urban network was largely unaffected by the industrialisation process, even though the proportion of city-dwellers rose from 17 to 45 per cent between 1831 and 1910. Especially in the Haine, Sambre and Meuse valleys, between the Borinage and Liège, where there was a huge industrial development based on coal-mining and iron-making, urbanisation was fast. During these eighty years the number of municipalities with more than 5,000 inhabitants increased from only 21 to more than one hundred, concentrating nearly half of the Walloon population in this region. Nevertheless, industrialisation remained quite traditional in the sense that it did not lead to the growth of modern and large urban centres, but to a conurbation of industrial villages and towns developed around a coal-mine or a factory. Communication routes between these small centres only became populated later and created a much less dense urban morphology than, for instance, the area around Liège where the old town was there to direct migratory flows.

France

The industrial revolution in France followed a particular course as it did not correspond to the main model followed by other countries. Notably, most French historians argue France did not go through a clear *take-off*. Instead, France's economic growth and industrialisation process was slow and steady through the 18th and 19th centuries. However, some stages were identified by Maurice Lévy-Leboyer:

- French Revolution and Napoleonic wars (1789–1815),
- industrialisation, along with Britain (1815–1860),
- economic slowdown (1860–1905),
- renewal of the growth after 1905.

Germany

Based on its leadership in chemical research in the universities and industrial laboratories, Germany, which was unified in 1871, became dominant in the world's chemical industry in the late 19th century. At first the production of dyes based on aniline was critical.

Germany's political disunity—with three dozen states—and a pervasive conservatism made it difficult to build railways in the 1830s. However, by the 1840s, trunk lines linked the major cities; each German state was responsible for the lines within its own borders. Lacking a technological base at first, the Germans imported their engineering and hardware from Britain, but quickly learned the skills needed to operate and expand the railways. In many cities, the new railway shops were the centres of technological awareness and training, so that by 1850, Germany was self-sufficient in meeting the demands of railroad construction, and the railways were a major impetus for the growth of the new steel industry. Observers found that even as late as 1890, their engineering was inferior to Britain's.

However, German unification in 1870 stimulated consolidation, nationalisation into state-owned companies, and further rapid growth. Unlike the situation in France, the goal was support of industrialisation, and so heavy lines crisscrossed the Ruhr and other industrial districts, and provided good connections to the major ports of Hamburg and Bremen. By 1880, Germany had 9,400 locomotives pulling 43,000 passengers and 30,000 tons of freight, and pulled ahead of France.

Sweden

During the period 1790–1815 Sweden experienced two parallel economic movements: an *agricultural revolution* with larger agricultural estates, new crops and farming tools and a commercialisation of farming, and a *protoindustrialisation*, with small industries being established in the countryside and with workers switching between agricultural work in summer and industrial production in winter. This led to economic growth benefiting large sections of the population and leading up to a *consumption revolution* starting in the 1820s. Between 1815 and 1850, the protoindustries developed into more specialised and larger industries. This period witnessed increasing regional specialisation with mining in Bergslagen, textile mills in Sjuhäradsbygden and forestry in Norrland. Several important institutional changes took place in this period, such as free and mandatory schooling introduced in 1842 (as the first country in the world), the abolition of the national monopoly on trade in handicrafts in 1846, and a stock company law in 1848.

From 1850 to 1890, Sweden experienced its "first" Industrial Revolution with a veritable explosion in export, dominated by crops, wood and steel. Sweden abolished most tariffs and other barriers to free trade in the 1850s and joined the gold standard in 1873. Large infrastructural investments were made during this period, mainly in the expanding rail road network, which was financed in part by the government and in part by private enterprises. From 1890 to 1930, new industries developed with their focus on the domestic market: mechanical engineering, power utilities, papermaking and textile.

Japan

The industrial revolution began about 1870 as Meiji period leaders decided to catch up with the West. The government built railroads, improved roads, and inaugurated a land reform programme to prepare the country for further development. It inaugurated a new Western-based education system for all young people, sent thousands of students to the United States and Europe, and hired more than 3,000 Westerners to teach modern science, mathematics, technology, and foreign languages in Japan (Foreign government advisors in Meiji Japan).

In 1871, a group of Japanese politicians known as the Iwakura Mission toured Europe and the United States to learn western ways. The result was a deliberate state-led industrialisation policy to enable Japan to quickly catch up. The Bank of Japan, founded in 1882, used taxes to fund model steel and textile factories. Education was expanded and Japanese students were sent to study in the west.

Modern industry first appeared in textiles, including cotton and especially silk, which was based in home workshops in rural areas.

United States

During the late 18th and early 19th centuries when the UK and parts of Western Europe began to industrialise, the US was primarily an agricultural and natural resource producing and processing economy. The building of roads and canals, the introduction of steamboats and the building of railroads were important for handling agricultural and natural resource products in the large and sparsely populated country of the period.

Important American technological contributions during the period of the Industrial Revolution were the cotton gin and the development of a system for making interchangeable parts, the latter aided by the development of the milling machine in the US. The development of machine tools and the system of interchangeable parts were the basis for the rise of the US as the world's leading industrial nation in the late 19th century.

Oliver Evans invented an automated flour mill in the mid-1780s that used control mechanisms and conveyors so that no labour was needed from the time grain was loaded into the elevator buckets until flour was discharged into a wagon. This is considered to be the first modern materials handling system an important advance in the progress toward mass production.

The United States originally used horse-powered machinery for small scale applications such as grain milling, but eventually switched to water power after textile factories began being built in the 1790s. As a result, industrialisation was concentrated in New England and the Northeastern United States, which has fast-moving rivers. The newer water-powered production lines proved more economical than horse-drawn production. In the late 19th century steam-powered manufacturing overtook water-powered manufacturing, allowing the industry to spread to the Midwest.

Thomas Somers and the Cabot Brothers founded the Beverly Cotton Manufactory in 1787, the first cotton mill in America, the largest cotton mill of its era, and a significant milestone in the research and development of cotton mills in the future. This mill was designed to use horse power, but the operators quickly learned that the horse-drawn platform was economically unstable, and had economic losses for years. Despite the losses, the Manufactory served as a playground of innovation, both in turning a large amount of cotton, but also developing the water-powered milling structure used in Slater's Mill.

In 1793, Samuel Slater (1768–1835) founded the Slater Mill at Pawtucket, Rhode Island. He had learned of the new textile technologies as a boy apprentice in Derbyshire, England, and defied laws against the emigration of skilled workers by leaving for New York in 1789, hoping to make money with his knowledge. After founding Slater's Mill, he went on to own 13 textile mills. Daniel Day established a wool carding mill in the Blackstone Valley at Uxbridge, Massachusetts in 1809, the third woollen mill established in the US (The first was in Hartford, Connecticut, and the second at Watertown, Massachusetts.) The John H. Chafee Blackstone River Valley National Heritage Corridor retraces the history of "America's Hardest-Working River', the Blackstone. The Blackstone River and its tributaries, which cover more than 70 kilometres (45 mi) from Worcester, Massachusetts to Providence, Rhode Island, was the birthplace of America's Industrial Revolution. At its peak over 1,100 mills operated in this valley, including Slater's mill, and with it the earliest beginnings of America's Industrial and Technological Development.

Merchant Francis Cabot Lowell from Newburyport, Massachusetts memorised the design of textile machines on his tour of British factories in 1810. Realising that the War of

1812 had ruined his import business but that a demand for domestic finished cloth was emerging in America, on his return to the United States, he set up the Boston Manufacturing Company. Lowell and his partners built America's second cotton-to-cloth textile mill at Waltham, Massachusetts, second to the Beverly Cotton Manufactory. After his death in 1817, his associates built America's first planned factory town, which they named after him. This enterprise was capitalised in a public stock offering, one of the first uses of it in the United States. Lowell, Massachusetts, using nine kilometres (5+1⁄2 miles) of canals and 7,500 kilowatts (10,000 horsepower) delivered by the Merrimack River, is considered by some as a major contributor to the success of the American Industrial Revolution. The short-lived utopia-like Waltham-Lowell system was formed, as a direct response to the poor working conditions in Britain. However, by 1850, especially following the Great Famine of Ireland, the system had been replaced by poor immigrant labour.

A major U.S. contribution to industrialisation was the development of techniques to make interchangeable parts from metal. Precision metal machining techniques were developed by the U.S. Department of War to make interchangeable parts for small firearms. The development work took place at the Federal Arsenals at Springfield Armory and Harpers Ferry Armory. Techniques for precision machining using machine tools included using fixtures to hold the parts in proper position, jigs to guide the cutting tools and precision blocks and gauges to measure the accuracy. The milling machine, a fundamental machine tool, is believed to have been invented by Eli Whitney, who was a government contractor who built firearms as part of this program. Another important invention was the Blanchard lathe, invented by Thomas Blanchard. The Blanchard lathe, or pattern tracing lathe, was actually a shaper that could produce copies of wooden gun stocks. The use of machinery and the techniques for producing standardised and interchangeable parts became known as the American system of manufacturing.

Precision manufacturing techniques made it possible to build machines that mechanised the shoe industry. and the watch industry. The industrialisation of the watch industry started 1854 also in Waltham, Massachusetts, at the Waltham Watch Company, with the development of machine tools, gauges and assembling methods adapted to the micro precision required for watches.

Second Industrial Revolution

- Steel is often cited as the first of several new areas for industrial mass-production, which are said to characterise a "Second Industrial Revolution", beginning around 1850, although a method for mass manufacture of steel was not invented until the 1860s, when Sir Henry Bessemer invented a new furnace which could convert molten pig iron into steel in large quantities. However, it only became widely available in the 1870s after the process was modified to produce more uniform quality. Bessemer steel was being displaced by the open hearth furnace near the end of the 19th century.

This Second Industrial Revolution gradually grew to include chemicals, mainly the chemical industries, petroleum (refining and distribution), and, in the 20th century, the automotive industry, and was marked by a transition of technological leadership from Britain to the United States and Germany.

The increasing availability of economical petroleum products also reduced the importance of coal and further widened the potential for industrialisation.

A new revolution began with electricity and electrification in the electrical industries. The introduction of hydroelectric power generation in the Alps enabled the rapid industrialisation of coal-deprived northern Italy, beginning in the 1890s.

By the 1890s, industrialisation in these areas had created the first giant industrial corporations with burgeoning global interests, as companies like U.S. Steel, General Electric, Standard Oil and Bayer AG joined the railroad and ship companies on the world's stock markets.

Causes

The causes of the Industrial Revolution were complicated and remain a topic for debate. Geographic factors include Britain's vast mineral resources. In addition to metal ores, Britain had the highest quality coal reserves known at the time, as well as abundant water power, highly productive agriculture, and numerous seaports and navigable waterways.

Some historians believe the Industrial Revolution was an outgrowth of social and institutional changes brought by the end of feudalism in Britain after the English Civil War in the 17th century, although feudalism began to break down after the Black Death of the mid 14th century, followed by other epidemics, until the population reached a low in the 14th century. This created labour shortages and led to falling food prices and a peak in real wages around 1500, after which population growth began reducing wages. Inflation caused by coinage debasement after 1540 followed by precious metals supply increasing from the Americas caused land rents (often long-term leases that transferred to heirs on death) to fall in real terms.

The Enclosure movement and the British Agricultural Revolution made food production more efficient and less labour-intensive, forcing the farmers who could no longer be self-sufficient in agriculture into cottage industry, for example weaving, and in the longer term into the cities and the newly developed factories.

The colonial expansion of the 17th century with the accompanying development of international trade, creation of financial markets and accumulation of capital are also cited as factors, as is the scientific revolution of the 17th century. A change in marrying patterns to getting married later made people able to accumulate more human capital during their youth, thereby encouraging economic development.

Until the 1980s, it was universally believed by academic historians that technological innovation was the heart of the Industrial Revolution and the key enabling technology was the invention and improvement of the steam engine. However, recent research into the Marketing Era has challenged the traditional, supply-oriented interpretation of the Industrial Revolution.

Lewis Mumford has proposed that the Industrial Revolution had its origins in the Early Middle Ages, much earlier than most estimates. He explains that the model for standardised mass production was the printing press and that "the archetypal model for the industrial era was the clock". He also cites the monastic emphasis on order and time-keeping, as well as the fact that medieval cities had at their centre a church with bell ringing at regular intervals as being necessary precursors to a greater synchronisation necessary for later, more physical, manifestations such as the steam engine.

The presence of a large domestic market should also be considered an important driver of the Industrial Revolution, particularly explaining why it occurred in Britain. In other nations, such as France, markets were split up by local regions, which often imposed tolls and tariffs on goods traded among them. Internal tariffs were abolished by Henry VIII of England, they survived in Russia until 1753, 1789 in France and 1839 in Spain.

Governments' grant of limited monopolies to inventors under a developing patent system (the Statute of Monopolies in 1623) is considered an influential factor. The effects of patents, both good and ill, on the development of industrialisation are clearly illustrated in the history of the steam engine, the key enabling technology. In return for publicly revealing the workings of an invention the patent system rewarded inventors such as James Watt by allowing them to monopolise the production of the first steam engines, thereby rewarding inventors and increasing the pace of technological development. However, monopolies bring with them their own inefficiencies which may counterbalance, or even overbalance, the beneficial effects of publicising ingenuity and rewarding inventors. Watt's monopoly prevented other inventors, such as Richard Trevithick, William Murdoch, or Jonathan Hornblower, whom Boulton and Watt sued, from introducing improved steam engines, thereby retarding the spread of steam power.

Causes in Europe

One question of active interest to historians is why the Industrial Revolution occurred in Europe and not in other parts of the world in the 18th century, particularly China, India, and the Middle East (which pioneered in shipbuilding, textile production, water mills, and much more in the period between 750 and 1100), or at other times like in Classical Antiquity or the Middle Ages. A recent account argued that Europeans have been characterized for thousands of years by a freedom-loving culture originating from the aristocratic societies of early Indo-European invaders. Many historians, however, have challenged this explanation as being not only Eurocentric, but also ignoring historical context. In fact, before the Industrial Revolution, "there existed something of a global economic parity between the most advanced regions in the world economy." These historians have suggested a number of other factors, including education, technological changes (see Scientific Revolution in Europe), "modern" government, "modern" work attitudes, ecology, and culture.

China was the world's most technologically advanced country for many centuries; however, China stagnated economically and technologically and was surpassed by Western Europe before the Age of Discovery, by which time China banned imports and denied entry to foreigners. China was also a totalitarian society. China also heavily taxed transported goods. Modern estimates of per capita income in Western Europe in the late 18th century are of roughly 1,500 dollars in purchasing power parity (and Britain had a per capita income of nearly 2,000 dollars) whereas China, by comparison, had only 450 dollars. India was essentially feudal, politically fragmented and not as economically advanced as Western Europe.

Historians such as David Landes and sociologists Max Weber and Rodney Stark credit the different belief systems in Asia and Europe with dictating where the revolution occurred. The religion and beliefs of Europe were largely products of Judaeo-Christianity and Greek thought. Conversely, Chinese society was founded on men like Confucius, Mencius, Han Feizi (Legalism), Lao Tzu (Taoism), and Buddha (Buddhism), resulting in very different worldviews. Other factors include the considerable distance of China's coal deposits, though large, from its cities as well as the then unnavigable Yellow River that connects these deposits to the sea.

Regarding India, the Marxist historian Rajani Palme Dutt said: "The capital to finance the Industrial Revolution in India instead went into financing the Industrial Revolution in Britain." In contrast to China, India was split up into many competing kingdoms after the decline of the Mughal Empire, with the major ones in its aftermath including the Marathas, Sikhs, Bengal Subah, and Kingdom of Mysore. In addition, the economy was highly dependent on two sectors—agriculture of subsistence and cotton, and there appears to have been little technical innovation. It is believed that the vast amounts of wealth were largely stored away in palace treasuries by monarchs prior to the British take over.

Economic historian Joel Mokyr argued that political fragmentation (the presence of a large number of European states) made it possible for heterodox ideas to thrive, as entrepreneurs, innovators, ideologues and heretics could easily flee to a neighboring state in the event that the one state would try to suppress their ideas and activities. This is what set Europe apart from the technologically advanced, large unitary empires such as China and India by providing "an insurance against economic and technological stagnation". China had both a printing press and movable type, and India had similar levels of scientific and technological achievement as Europe in 1700, yet the Industrial Revolution would occur in Europe, not China or India. In Europe, political fragmentation was coupled with an "integrated market for ideas" where Europe's intellectuals used the *lingua franca* of Latin, had a shared intellectual basis in Europe's classical heritage and the pan-European institution of the Republic of Letters.

In addition, Europe's monarchs desperately needed revenue, pushing them into alliances with their merchant classes. Small groups of merchants were granted monopolies and tax-collecting responsibilities in exchange for payments to the state. Located in a region "at the hub of the largest and most varied network of exchange in history," Europe advanced as the leader of the Industrial Revolution. In the Americas, Europeans found a windfall of silver, timber, fish, and maize, leading historian Peter Stearns to conclude that "Europe's Industrial

Revolution stemmed in great part from Europe's ability to draw disproportionately on world resources."

Modern capitalism originated in the Italian city-states around the end of the first millennium. The city-states were prosperous cities that were independent from feudal lords. They were largely republics whose governments were typically composed of merchants, manufacturers, members of guilds, bankers and financiers. The Italian city-states built a network of branch banks in leading western European cities and introduced double entry bookkeeping. Italian commerce was supported by schools that taught numeracy in financial calculations through abacus schools.

Causes in Britain

Great Britain provided the legal and cultural foundations that enabled entrepreneurs to pioneer the Industrial Revolution. Key factors fostering this environment were:

- The period of peace and stability which followed the unification of England and Scotland
- There were no internal trade barriers, including between England and Scotland, or feudal tolls and tariffs, making Britain the "largest coherent market in Europe"
- The rule of law (enforcing property rights and respecting the sanctity of contracts)
- A straightforward legal system that allowed the formation of joint-stock companies (corporations)
- Free market (capitalism)

- Geographical and natural resource advantages of Great Britain were the fact that it had extensive coastlines and many navigable rivers in an age where water was the easiest means of transportation and Britain had the highest quality coal in Europe. Britain also had a large number of sites for water power.

There were two main values that really drove the Industrial Revolution in Britain. These values were self-interest and an entrepreneurial spirit. Because of these interests, many industrial advances were made that resulted in a huge increase in personal wealth and a consumer revolution. These advancements also greatly benefitted the British society as a whole. Countries around the world started to recognise the changes and advancements in Britain and use them as an example to begin their own Industrial Revolutions.

The debate about the start of the Industrial Revolution also concerns the massive lead that Great Britain had over other countries. Some have stressed the importance of natural or financial resources that Britain received from its many overseas colonies or that profits from the British slave trade between Africa and the Caribbean helped fuel industrial investment. However, it has been pointed out that slave trade and West Indian plantations provided only 5% of the British national income during the years of the Industrial Revolution. Even though slavery accounted for so little, Caribbean-based demand accounted for 12% of Britain's industrial output.

- Instead, the greater liberalisation of trade from a large merchant base may have allowed Britain to

> produce and use emerging scientific and technological developments more effectively than countries with stronger monarchies, particularly China and Russia. Britain emerged from the Napoleonic Wars as the only European nation not ravaged by financial plunder and economic collapse, and having the only merchant fleet of any useful size (European merchant fleets were destroyed during the war by the Royal Navy). Britain's extensive exporting cottage industries also ensured markets were already available for many early forms of manufactured goods. The conflict resulted in most British warfare being conducted overseas, reducing the devastating effects of territorial conquest that affected much of Europe. This was further aided by Britain's geographical position—an island separated from the rest of mainland Europe.

Another theory is that Britain was able to succeed in the Industrial Revolution due to the availability of key resources it possessed. It had a dense population for its small geographical size. Enclosure of common land and the related agricultural revolution made a supply of this labour readily available.

There was also a local coincidence of natural resources in the North of England, the English Midlands, South Wales and the Scottish Lowlands. Local supplies of coal, iron, lead, copper, tin, limestone and water power resulted in excellent conditions for the development and expansion of industry. Also, the damp, mild weather conditions of the North West of England provided ideal conditions for the spinning of cotton, providing a natural starting point for the birth of the textiles industry.

The stable political situation in Britain from around 1688 following the Glorious Revolution, and British society's greater receptiveness to change (compared with other European countries) can also be said to be factors favouring the Industrial Revolution. Peasant resistance to industrialisation was largely eliminated by the Enclosure movement, and the landed upper classes developed commercial interests that made them pioneers in removing obstacles to the growth of capitalism. (This point is also made in Hilaire Belloc's *The Servile State*.)

The French philosopher Voltaire wrote about capitalism and religious tolerance in his book on English society, *Letters on the English* (1733), noting why England at that time was more prosperous in comparison to the country's less religiously tolerant European neighbours. "Take a view of the Royal Exchange in London, a place more venerable than many courts of justice, where the representatives of all nations meet for the benefit of mankind. There the Jew, the Mahometan [Muslim], and the Christian transact together, as though they all professed the same religion, and give the name of infidel to none but bankrupts. There the Presbyterian confides in the Anabaptist, and the Churchman depends on the Quaker's word. If one religion only were allowed in England, the Government would very possibly become arbitrary; if there were but two, the people would cut one another's throats; but as there are such a multitude, they all live happy and in peace."

Britain's population grew 280% 1550–1820, while the rest of Western Europe grew 50–80%. Seventy percent of European urbanisation happened in Britain 1750–1800. By 1800, only the Netherlands was more urbanised than Britain. This was only possible because coal, coke, imported cotton, brick and slate had replaced wood, charcoal, flax, peat and thatch. The latter compete with land grown to feed people while mined materials do not. Yet more land would be freed when chemical fertilisers replaced manure and horse's work was mechanised. A workhorse needs 1.2 to 2.0 ha (3 to 5 acres) for fodder while even early steam engines produced four times more mechanical energy.

In 1700, five-sixths of the coal mined worldwide was in Britain, while the Netherlands had none; so despite having Europe's best transport, lowest taxes, and most urbanised, well-paid, and literate population, it failed to industrialise. In the 18th century, it was the only European country whose cities and population shrank. Without coal, Britain would have run out of suitable river sites for mills by the 1830s. Based on science and experimentation from the continent, the steam engine was developed specifically for pumping water out of mines, many of which in Britain had been mined to below the water table. Although extremely inefficient they were economical because they used unsaleable coal. Iron rails were developed to transport coal, which was a major economic sector in Britain.

Economic historian Robert Allen has argued that high wages, cheap capital and very cheap energy in Britain made it the ideal place for the industrial revolution to occur. These factors made it vastly more profitable to invest in research and development, and to put technology to use in Britain than other societies. However, two 2018 studies in *The Economic History Review* showed that wages were not particularly high in the British spinning sector or the construction sector, casting doubt on Allen's explanation.

Transfer of knowledge

Knowledge of innovation was spread by several means. Workers who were trained in the technique might move to another employer or might be poached. A common method was for someone to make a study tour, gathering information where he could. During the whole of the Industrial Revolution and for the century before, all European countries and America engaged in study-touring; some nations, like Sweden and France, even trained civil servants or technicians to undertake it as a matter of state policy. In other countries, notably Britain and America, this practice was carried out by individual manufacturers eager to improve their own methods. Study tours were common then, as now, as was the keeping of travel diaries. Records made by industrialists and technicians of the period are an incomparable source of information about their methods.

Another means for the spread of innovation was by the network of informal philosophical societies, like the Lunar Society of Birmingham, in which members met to discuss 'natural philosophy' (*i.e.* science) and often its application to manufacturing. The Lunar Society flourished from 1765 to 1809, and it has been said of them, "They were, if you like, the revolutionary committee of that most far reaching of all the eighteenth century revolutions, the Industrial Revolution". Other such societies published volumes of proceedings and transactions. For example, the London-based Royal Society of

Arts published an illustrated volume of new inventions, as well as papers about them in its annual *Transactions*.

There were publications describing technology. Encyclopaedias such as Harris's *Lexicon Technicum* (1704) and Abraham Rees's *Cyclopaedia* (1802–1819) contain much of value. *Cyclopaedia* contains an enormous amount of information about the science and technology of the first half of the Industrial Revolution, very well illustrated by fine engravings. Foreign printed sources such as the *Descriptions des Arts et Métiers* and Diderot's *Encyclopédie* explained foreign methods with fine engraved plates.

Periodical publications about manufacturing and technology began to appear in the last decade of the 18th century, and many regularly included notice of the latest patents. Foreign periodicals, such as the *Annales des Mines*, published accounts of travels made by French engineers who observed British methods on study tours.

Protestant work ethic

Another theory is that the British advance was due to the presence of an entrepreneurial class which believed in progress, technology and hard work. The existence of this class is often linked to the Protestant work ethic (see Max Weber) and the particular status of the Baptists and the dissenting Protestant sects, such as the Quakers and Presbyterians that had flourished with the English Civil War. Reinforcement of confidence in the rule of law, which followed establishment of the prototype of constitutional monarchy in Britain in the Glorious Revolution of 1688, and the emergence of a stable financial market there based on the management of the national debt by the Bank of England, contributed to the capacity for, and interest in, private financial investment in industrial ventures.

Dissenters found themselves barred or discouraged from almost all public offices, as well as education at England's only two universities at the time (although dissenters were still free to study at Scotland's four universities). When the restoration of the monarchy took place and membership in the official Anglican Church became mandatory due to the Test Act, they thereupon became active in banking, manufacturing and education.

The Unitarians, in particular, were very involved in education, by running Dissenting Academies, where, in contrast to the universities of Oxford and Cambridge and schools such as Eton and Harrow, much attention was given to mathematics and the sciences – areas of scholarship vital to the development of manufacturing technologies.

Historians sometimes consider this social factor to be extremely important, along with the nature of the national economies involved. While members of these sects were excluded from certain circles of the government, they were considered fellow Protestants, to a limited extent, by many in the middle class, such as traditional financiers or other businessmen. Given this relative tolerance and the supply of capital, the natural outlet for the more enterprising members of these sects would be to seek new opportunities in the technologies created in the wake of the scientific revolution of the 17th century.

Criticisms

The Industrial revolution has been criticised for complete ecological collapse, causing mental illness, pollution and unnatural systems of organizing for humanity. Since the start of the industrial revolution people have criticised it by stating the Industrial Revolution turned humanity and nature into slaves and destroying the world. It has also been criticised by valuing profits and corporate growth over life and wellbeing, multiple movements have arose philosophically against the Industrial revolution and include groups such as the Amish and Primitivism.

Individualism humanism and industrial slavery

Humanists, and individualists criticise the Industrial revolution for turning humans into Industrial slaves, that humans lack autonomy in a modern industrialised world. Critics of the Industrial revolution state that humanity is perpetually controlled by technology and commanded by technology such as the computer mandated work, and that any individual freedom is destroyed by industrialisation.

Primitivism

Primitivism argues that the Industrial Revolution have created an un-natural frame of society and the world in which humans need to adapt to an un-natural urban landscape in which humans are perpetual cogs without personal autonomy.

Certain primitivists argue for a return to pre-industrial society, while others argue that technology such as modern medicine, and agriculture are all positive for humanity assuming they controlled and serve humanity and have no effect on the natural environment.

Pollution and ecological collapse

The Industrial revolution has been criticised for leading to immense ecological and habitat destruction, certain studies state that over 95% of species have gone extinct since humanity became the dominant species on earth. It has also led to immense decrease in the biodiversity of life on earth. The Industrial revolution has been stated as is inherently unsustainable and will lead to eventual collapse of society, mass hunger, starvation, and resource scarcity.

The Anthropocene

The Anthropocene is a proposed epoch or mass extinction coming from humanity (Anthro is the Greek root for humanity). Since the start of the Industrial revolution humanity has permanently changed the earth, such as immense decrease in biodiversity, and mass extinction caused by the Industrial revolution. The effects include permanent changes to the earth's atmosphere and soil, forests, the mass destruction of the Industrial revolution has led to catastrophic impacts on the earth. Most organisms are unable to adapt leading to mass extinction with the remaining undergoing evolutionary rescue, as a result of the Industrial revolution.

Permanent changes in the distribution of organisms from human influence will become identifiable in the geologic record. Researchers have documented the movement of many species into regions formerly too cold for them, often at rates faster than initially expected. This has occurred in part as a result of changing climate, but also in response to farming and fishing, and to the accidental introduction of non-native species to new areas through global travel. The ecosystem of the entire Black Sea may have changed during the last 2000 years as a result of nutrient and silica input from eroding deforested lands along the Danube River.

Opposition from Romanticism

During the Industrial Revolution, an intellectual and artistic hostility towards the new industrialisation developed, associated with the Romantic movement. Romanticism revered the traditionalism of rural life and recoiled against the upheavals caused by industrialization, urbanization and the wretchedness of the working classes. Its major exponents in English included the artist and poet William Blake and poets William Wordsworth, Samuel Taylor Coleridge, John Keats, Lord Byron and Percy Bysshe Shelley. The movement stressed the importance of "nature" in art and language, in contrast to "monstrous" machines and factories; the "Dark satanic mills" of Blake's poem "And did those feet in ancient time". Mary Shelley's *Frankenstein* reflected concerns that scientific progress might be two-edged. French Romanticism likewise was highly critical of industry.