Chapter 5

The Industrial Revolution

The period of rapid change from manual production to machine production, and from cottage to factory, in the 18th and 19th centuries is usually referred to as the industrial revolution. In view of later major technological upheavals, it is now often referred to as the first industrial revolution. The dating of this period, as of all historical periods, is arbitrary and imprecise. Some historians like to extend the period from 1750 to 1900; others prefer somewhat shorter periods. The industrial revolution started in England and was confined to England during its first phase, from about 1760 to about 1830. It was a period when invention chased invention and when large, mechanised, textile and steel industries were built up. Coal and steam provided the energy to drive the new machinery and, hence, coal mining expanded dramatically. It was also the beginning of the railway age, with all its economic and social repercussions, not to mention the military implications. The social changes accompanying the technological change were of far-reaching importance. A new class arose: the working class or proletariat. The middle class expanded by the addition of owners and investors, managers, and professionals based on industry. The new factories drew workers away from the countryside into new or growing cities. Factories provided work of sorts and the landless poor followed their call. Industry provided new opportunities for entrepreneurs and for investors, as well as for higher echelons of workers: managers, engineers, and all the professional and commercial services that go with new or vastly enlarged population centres.

The following summary of the main features of the industrial revolution should provide a general overview of what it was all about. The three main technological developments were:

1. The rise of the factory system of production, particularly in the textile industry;
2. The development of the steam engine as a prime mover and, as a consequence, the development of the railways and an increased demand for coal;
3. The development of iron smelting that made it possible to substitute coke for charcoal and led to a huge increase in iron and steel production. This development is associated with a further increase in demand for coal and the development of town gas.

The associated social developments were:

1. The rise of the industrial city;
2. The rise of an industrial workforce and thus a working class or proletariat;
3. A vast expansion in total consumption of manufactured goods.

The era ushered in by the industrial revolution has not really ended. We still live in an industrial society, though many commentators prefer to call our age post-industrial because industry no longer provides the main source of employment. However, we still produce in factories; we still use power, though now mostly electric power, to drive production machinery, and consumption of manufactured products has continued to expand. Agriculture has continued to lose workers, albeit no longer to industry but to the service sector.

The intellectual climate had changed radically between the end of the Middle Ages and the dawning of the Industrial Age. It all began with the Renaissance and continued with the birth of modern science in the 17th century and the Enlightenment of the 18th century. The 16th, 17th and 18th centuries may be viewed as a continuous period of intellectual change from dogma to freedom. Whereas at the beginning of the period church dogma reigned supreme and intellectual activity outside these strict boundaries was non-existent; at the end of the period intellectual activity ranged freely over all aspects of human activity. Philosophy, natural science, medicine, and art had all thrown off the shackles of dogma and allowed the spirit of enquiry to range freely. The Renaissance, the birth of modern science and of Empiricism, the Enlightenment, all these are phases and movements contributing to freedom of thought, to the deposition of the church from its position as the sole arbiter of all truth and, ultimately, to a leading role for rationality and science. It did not happen without a struggle and the process has never been completed. In fact in these days of religious fundamentalism and fanaticism, one might think that we have been moving backward in recent years.

At the beginning of the period the church still reigned supreme and fought hard to retain its supremacy. One of the toughest battles was that for the central position of the Earth. To the church, this was of supreme importance because the Earth was the centrepiece of God's creation and thus had to be the centre of the universe. The Greek philosopher Aristotle (384 to 322 BC) postulated that the Earth had to be stationary and could not rotate. The later Greek astronomer Ptolemy (2nd century AD) devised an ingenious astronomical model in which the known stars were fixed to a system of crystal spheres revolving in complex motions, with the Earth at the centre of the spheres – the geocentric universe. The church accepted Aristotle's writings and Ptolemy's theory as incontrovertibly correct and not open to doubt. When astronomers of the 16th century, led by Nicolaus Copernicus (born c.1473), suggested that the Earth might not be the centre of the universe but was merely one of several planets revolving round the sun – the heliocentric universe - the church fought long and hard to preserve it geocentric view. The first publication suggesting the heliocentric system was De Revolutionibus by Nicolaus Copernicus, published in 1543. Brave men of science fought protracted battles; sometimes ending in the execution of the scientist branded a heretic, against a church that refused to accept new scientific thinking and interpreted its own dogmatic view of the world in the narrowest possible way. Galileo Galilei (1564–1642) regarded as the founder of experimental science, spent years battling the church and had the narrowest of escapes from extreme punishment, because his writings, though couched in most cautious language, were regarded as supporting the Copernican view. Galileo, one of the earliest scientists to use a telescope for astronomical observation, had concluded from his observations that the Ptolemaic theory was untenable and that the much simpler Copernican theory ought to be accepted. After protracted battles the church eventually accepted that science and religion could be reconciled, though many think that, at best, they can only co-exist peacefully, without real compatibility. This was not Newton's view. Isaac Newton (1642–1727) stressed repeatedly that his motivation for scientific research was the wish to fathom the ways God had constructed the world and thus learn more of God's will. Not many scientists are driven by this motivation in the present day.

Giants of science, beginning with Galileo and perhaps culminating with Isaac Newton, succeeded in showing that science could lead to an understanding of natural phenomena by using experiment and observation as the foundation for theoretical thought and mathematical argument. Science refuted the view, held by Greek philosophers, that logical argument alone could furnish scientific knowledge; knowledge had to be based on observation, and observation had to be the arbiter of correctness of scientific theory. In consequence of this changed intellectual attitude, science developed by leaps and bounds. Newton laid the foundations to calculus, showed that white light consisted of a mixture of light of all possible wavelengths (and thus colours), and discovered both the law of gravity and the fundamental laws of motion. These achievements were made possible by previous experiments and theories of motion (mechanics) by Galileo and the wave theory of light proposed by Christian Huygens (1629–1695).

Though science and technology were not nearly as interwoven and as interdependent as they are in our modern day, I think that there was a great deal of interaction even in the days of nascent experimental science. Technology enabled experimental science to advance and scientific knowledge helped technology to develop. Technology had progressed sufficiently to provide the equipment necessary for scientific experimentation. Lenses and mirrors could be ground for the construction of telescopes and microscopes; prisms could be manufactured to investigate the nature of light, and machinery could be devised to test properties of materials and of gases. Astronomy made great strides in the wake of the introduction of the telescope into astronomical observation, mainly owing to Galileo and to Newton, but also several others. Indeed by mentioning a few names one does great injustice to the many important scientists who remain without a mention. Machines could be constructed with greater confidence owing to the knowledge of the laws of motion on the one hand, and knowledge of the properties of materials owed in those days to Robert Hooke (1635–1703) and his law of elasticity. Biology began to make great strides when Antonie van Leeuwenhoek (1632–1723) built a microscope and discovered the existence of bacteria. Finally, I shall mention Robert Boyle (1627–1691) and Blaise Pascal (1623–1662) who discovered the fundamental laws of the behaviour of gases. This was important, perhaps crucial, for the construction of steam engines.

This amazing bunching of scientific genius in so short a time is rather surprising and calls for some, albeit speculative, explanation. I think that two factors were involved.

First, the church had given up its resistance to scientific thinking. The scientific trailblazers, such as Nicolaus Copernicus and Galileo Galilei, as well as the philosophers and scholars of the Renaissance, had shaken off the intellectual shackles of the church and had achieved a degree of independence of thought and of teaching and learning. Secondly, the general level of economic and social development had brought into being an educated and affluent middle class of merchants and professional men who had sufficient leisure, and sufficient means, to follow intellectual pursuits. It was no longer necessary for almost everybody to engage in agriculture in order to feed the population, and the landowners were no longer the only wealthy and influential class. Universities had been founded in which such men could pursue their researches without intellectual or financial dependence.

Finally, the Enlightenment, though essentially a movement of the 18th century, had truly started in the late 17th century and was, in part at least, a movement for education of a large lay public. Societies for reading and learning and a variety of discussion groups sprang up everywhere and formed a popular counterpart to the founding of learned societies. The learned societies, that were to become prestigious and illustrious institutions, predated the discussion groups and were founded in the second half of the 17th century. The Royal Society of London for the Promotion of Natural Knowledge was founded in 1660 and given a Royal Charter by Charles II in 1662. Of equal importance was the French Academy of Sciences (Académie des Sciences), founded in 1666. Huygens was among the founding members, as were Rene Descartes, Blaise Pascal, and many other illustrious men. One of the moving spirits behind the foundation of the Academy was Jean-Baptiste Colbert, at the time controller general of finance. This shows the involvement of the state as a benefactor of science and proves that since that crucial period science has not only been tolerated, but also actively encouraged. The Prussian Academy of Sciences was not far behind. It was founded in 1700 under King Frederick I and its first president was the famous philosopher and mathematician Gottfried Wilhelm Leibniz (1646–1716).

"For the German philosopher Immanuel Kant, Enlightenment was mankind's final coming of age, the emancipation of the human consciousness from an immature state of ignorance and error"[1]. The encyclopédists Diderot and d'Alembert were of major influence in the Enlightenment, along with many other philosophers in several countries. A full list would be tantamount to a who-is-who of the time and I shall name but a few for general orientation: Montesquieu, Voltaire, Locke, Hume, Rousseau, Kant, Herder, Benjamin Franklin and perhaps Thomas Paine. The Encyclopédie defines the *philosophe* as one who 'trampling on prejudice, tradition, universal consent, authority, in a word, all that enslaves most minds, dares to think for himself.'[2] "…Christianity was ever after with its back against the wall, forever trying to accommodate itself to new knowledge. The Enlightenment by contrast eagerly seized upon the excitement of the infinite."[3]

It was an age of readiness for experimentation and new ventures. There was a new curiosity about the world, which gave rise to new scientific theories and to new mathematics. And there was a new willingness to experiment with new ideas in engineering and in economic enterprise. The scientific knowledge and the intellectual climate were ready for the scientific and the industrial revolutions. And a new bourgeois class was ready to become the social carrier of revolutionary change.

Although the great inventors of the day were not men of science but men of practical experience, this is not to say that they were unaware of scientific knowledge. They may not have been formally educated, but they were

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1 See Roy Porter, (2001), The Enlightenment, Palgrave, p. 1
2 Ibid, p. 3
3 Ibid, p. 67

self-taught, knowledgeable and imaginative men. Both during the industrial revolution and in the preceding period that we might describe as the scientific revolution, interchange between scientists and inventors was active. Many private discussion groups made important contributions and made sure that knowledge was disseminated, deepened by discussion and kept alive as a social enterprise.

Unfortunately, not all exchanges among scientists were friendly and constructive. Some extraordinarily acrimonious disputes are known. Robert Hooke and Isaac Newton had many a quarrel, both as to the validity of their scientific theories and as to priority of discovery. The most famous dispute of all was between Newton and Leibniz. The main bone of contention between them was priority in the invention of the calculus. It seems certain that both men had in fact invented it independently in slightly different form. The dispute was as bitter as it was protracted and was never resolved by the disputants.

The spirit of free enquiry and free enterprise spread throughout Europe and America and so did the Industrial Revolution. Though England made strenuous efforts to keep the new inventions and the new skills confined to England, that effort was doomed to failure. Other countries began to imitate the English success, sometimes with the aid of English entrepreneurs. The first country that followed the English example in building up large steel, coal, and textile industries was Belgium. France took a little longer, as in the early phase of the industrial revolution it was in the throes of political revolution and of war. Germany also proved tardy in the beginning and did not start to develop fast till after the unification of Germany in 1871. More countries followed: the United States, Netherlands, Sweden, Austria-Hungary, Italy and, especially after the Bolshevik revolution, the Soviet Union. By the middle of the 20th century, almost the whole world, including Japan, China and India, was industrialized.

Many conditions have to be fulfilled for such major technological change to take place in such a short period, indeed for the change to begin and feed on itself and gather pace.

The first condition is the existence of an efficient agriculture, capable of feeding a growing proportion of the population that is not actively engaged on food production. Only an efficient agriculture can free sufficient labour to enable industrial production to grow. Associated with this condition is the possibility for the rural population to move freely into the growing industrial centres, to provide the new industrial labour force. In feudal times, when agricultural workers were prohibited from moving, industrialisation was not possible, unless the landowners had undertaken it. Considerable improvements in the efficiency and productivity of agriculture indeed preceded the Industrial Revolution.

The second condition was a sufficiently large and developed pre-industrial manufacturing base. Without such a base, there would not have been the reservoir of skills and experience necessary for embarking upon the Industrial Revolution. Fairly large quantities of textiles were produced on simple hand operated machines. A variety of machinery, including forges, pumps, bellows and flourmills, were driven by water- animal- or wind-power. Substantial quantities of iron, copper, brass, bronze and other metals and alloys were produced and a variety of objects were manufactured from them. The pottery industry operated on quite a large scale. Building and civil engineering had progressed to quite a high level and transport was reasonably well developed. The production and consumption of non-agricultural goods had reached a substantial level. In association with all these developments, many skilled craftsmen had been trained in a variety of industrially relevant trades.

The third condition was the existence of a class of people who had capital at their disposal and were flexible enough and mobile enough to try their hand at a variety of enterprises. Traders and merchants who had accumulated some capital and were looking for new commercial opportunities were as important as bankers who were looking for profitable investments and profitable possibilities of lending out their money. It was necessary that the newly rich, and perhaps some of the older rich, were prepared to risk their money on entrepreneurial enterprises and did not aspire to live a life of leisure and luxury. They were prepared to spend money on uncertain enterprise, rather than squandering it all on building palaces, acquiring land, and consuming luxury items such as jewellery and silverware.

Finally, it was necessary for a number of craftsmen to be not only skilled, but also generally educated, intelligent and imaginative enough to see new technological possibilities that might improve existing products or improve the ways existing products were manufactured. In short, a class of inventors and technical entrepreneurs was required.

To recapitulate: the industrial revolution was possible only because agriculture was efficient and could spare labour; the rural population became mobile; there was an adequate accumulation of capital that was available for risky enterprises; there was a sufficient reservoir of skills; and there were some highly gifted and imaginative craftsmen who provided the inventions for the new age.

It is said that the entrepreneurial spirit was particularly strong in England as opposed to, for example, the predilection toward luxury among the French elite of the time. Some argue that the Protestant faith had something to do with a propensity for hard work, rather than leanings toward excessive luxury and the ornate baroque or rococo styles. The so-called Protestant work ethic and the leanings toward austerity and puritanism, might have contributed to the industrial revolution in England and leanings toward luxury might have contributed to its delayed start elsewhere. The arguments concerning the Protestant work ethic, though often used, are not entirely convincing, though they might contain a grain of truth. What is beyond doubt is that a dogmatic religion that demands excessive obedience from its believers does discourage free thought and an entrepreneurial spirit. Similarly, an excessively hierarchical and dictatorial political system puts a brake on inventiveness and on the taking of entrepreneurial risks. In an oppressive regime it is politically too risky to take commercial or technical risks. Considerations of this ilk apply to the Middle Ages and still apply to some countries or sections of the population in the modern world. They may well be contributing causes to the geographic distribution of modern technological, industrial and commercial success.

The textile industry was the largest of all medieval industries, both in terms of labour employed and in terms of turnover and trade. By the time of the industrial revolution, the industry was producing a large amount of cotton cloth in addition to the traditional woollen and linen cloth. In the decade 1750-59 Britain imported 2.81 million lb (about 1.3 thousand tonnes) of raw cotton annually. A hundred years later, in the decade 1850-59, annual imports had risen to 795 million lb (360,000 tonnes). The textile industry was the one that was first affected by the great inventions and innovations of the industrial revolution. Spinning was the bottleneck of the industry. The weavers were crying out for more yarn that the spinners were hard put to provide. From the technical point of view, spinning is a simpler operation than weaving and on both these counts it is not surprising that the famous great inventions in the textile industry started off with spinning machines.

The first spinning machine was the 'spinning jenny', invented by James Hargreaves in 1766. The spinning jenny was still hand-operated, but instead of spinning a single yarn, it could spin several yarns simultaneously and thus massively increased the output of each worker. The quality of the yarn was not very good and it was suitable only for the weft, not for the warp. The next improvement came from the so-called water frame, a spinning machine driven by water power and producing a high quality of cotton thread. It was invented in 1769 by Richard Arkwright. Arkwright was more than an inventor; he was the first industrialist who introduced the factory system of production that replaced the earlier system of 'putting out' work to small cottage industries. Generally a small merchant put out the work to families based on rural cottages. All members of the family could contribute. The merchant supplied the materials, managed the sequence of processes and marketed the finished products. By 1782 Arkwright employed 5,000 workers in his factory. The third famous name among inventors of spinning machines is that of Samuel Crompton, who invented the spinning mule in 1779. The mule was similar to the spinning jenny, except that it was power-driven and not only spun but also drew out and twisted the cotton yarn simultaneously, thus improving its quality. Crompton's mule, reputedly so called because it was a cross between the spinning jenny and the water frame, found almost universal application, as it enabled the mass production of cotton yarn of high quality. Alas Crompton himself obtained only a minute share of the success because he lacked the money to patent his machine and was cheated out of promised royalties. By 1812 there were 360 mills in operation in Britain, using 4,600,000 mule spindles.

The true importance of these inventions is not simply an increase in the productivity of spinners, but the fact that the whole system of 'putting out' was replaced by a factory system. This was necessitated by the fact that the new machines were expensive and large and needed a source of power, and were thus unsuitable for a small cottage industry. The repercussions of the factory system were far-reaching. Large factories were built that employed thousands of workers. This required major capital inputs and new management skills. It also meant that the workers had to move out of the countryside into the vicinity of the factories, and that only the employed worker earned money while the rest of the family could no longer contribute to the family's income.

It further meant that the worker had to submit to the discipline imposed by machines and by managers and had to learn new skills. Some of the former merchants, who had acted as putters-out, saw organisational advantages in the factory system. By centralising the flows of goods into and out of the factory they gained better control over the goods, and by centralising the workers they gained better control over the workforce. The confluence of large machines and administrative advantage commended the factory system to the capitalist to the point of irresistibility. Finally, it meant that a lot of the input into the textile manufacturing industry now came from outside, for example from the designers and manufacturers of the machinery, though some textile manufacturers, such as Arkwright, made their own. In the longer run, conflicts between the emerging industrial working class and the capitalist/industrialist class were inevitable. Whereas previously nascent capitalism was based on successful merchants and bankers, the bourgeois class was now joined by the industrialists. And what were previously independent small tradesmen/manufacturers became threatened in their existence. Some trades continued to flourish – and indeed flourish to the present day – others had the option of quitting and becoming labourers or, possible only for a very few, to join the class of industrial entrepreneurs.

The power-driven mechanical loom inevitably had to follow the spinning machine. As the bottleneck of spinning was removed, the next bottleneck in textile manufacture, the process of weaving, reared its head. The first successful power-loom was invented by Edmund Cartwright in 1785. It was driven by horses at first, but these were replaced by steam power in 1789. Cartwright's factory was burned down in 1791 by weavers fearing for their livelihood, but the loom continued on its path of gradually replacing handlooms. Though in 1834 there were still twice as many handlooms as power-looms (which says nothing about the ratio of their outputs), by 1850 the power-loom had completely replaced the handloom in Britain. The introduction of power looms was not as rapid as might have been expected. This is explained by two factors. First, the investment took a few years to bring substantial financial benefits and thus needed strong financial muscle as well as foresight. Secondly, the weavers on handlooms were prepared to put up with lower and lower incomes rather than give up their skilled trade and were thus able to compete with the industrially manufactured cloth for quite some time, albeit at the cost of starvation.

The innovations described so far would have left the revolution in textile manufacture incomplete. The bottleneck of spinning was removed by the new steam-powered spinning machines and weaving was greatly accelerated by powered mechanical looms. The increased quantities of cloth still had to be finished to give them a pleasant appearance and touch. The most important of the finishing processes was bleaching, thereby turning the unsightly greyish material white and ready to be dyed and printed. Removing the weakest link from a chain reveals the next weakness. These finishing processes formed a new bottleneck that could only be removed by developments in the chemical industry.

The Swedish chemist Carl Wilhelm Scheele discovered chlorine in 1774, and its bleaching properties provided the solution to the bleaching bottleneck for cotton cloth. The original method of bleaching was to spread the cloth on the ground and expose it to sunshine. Unfortunately sunshine is a pretty scarce commodity in the British Isles and, with rapidly increasing production of cotton cloth, the demand on space for bleaching could not be met. More importantly, the old method of bleaching was hardly suitable for factory production. Thus the discovery of the bleaching properties of chlorine and its various compounds were eagerly seized upon.

Perhaps the most quintessential feature of the industrial revolution was the introduction of steam as a prime mover. Whereas previously machines were either operated by human power, animal power or waterpower, a new prime mover became available that was far more powerful than human or animal power and, in contrast to waterpower, was not restricted to locations near suitable streams.

Steam power has many antecedents. The physicist Denis Papin demonstrated the pressure steam can exert and suggested some kind of steam engine with a piston moved by the pressure of steam. This never progressed beyond a model, and Papin is remembered mainly as the father of the pressure cooker and its safety valve. The concept and magnitude of atmospheric pressure were elucidated by Galileo's assistant and successor as professor of mathematics at the Florentine Academy, Evangelista Torricelli, who first measured atmospheric pressure and by Blaise Pascal, who measured the change in atmospheric pressure as a function of the height above sea level.

The most impressive practical demonstration of the forces involved was arranged in 1654 by Otto von Guericke, an outstanding engineer and successful politician and, it would appear, a brilliant showman. Having invented a mechanical vacuum pump, he evacuated the sphere enclosed between two hollow copper hemispheres, fitted together with an airtight seal. In one of the most spectacular public scientific demonstrations in history, he employed eight horses to attempt pulling the so-called Magdeburg hemispheres apart. Although they were held together merely by the pressure of the atmosphere and were only about 14 inches (35cm) in diameter, the horses failed in their attempt, thus demonstrating the tremendous force exerted by the atmosphere. The designers of the first steam engines made good use of this knowledge and let atmospheric pressure do most of the work of the engine.

Thomas Savery produced a steam-driven pump. The pump consisted of a steam boiler that filled a vessel with steam. When the vessel was cooled so that the steam would condense, a vacuum was created that could be used to raise water into the vessel. As atmospheric pressure can raise water to no more than just under 10m, Savery used high-pressure steam to drive the water from the first vessel into a higher one. It is said that the pump was able to raise water to a height of 80 feet (about 25m). Although Savery's patent, granted in 1698, mentioned "Raising of Water and occasioning Motion to all Sorts of Mill Work by the Impellent Force of Fire", his device was merely a water pump without moving parts (except valves). Pumping water from mines was an important task and Savery's pump achieved this with greater efficiency than all the predecessor, usually horse-driven, devices. Because of the comprehensive nature of Savery's patent, the inventor of the first piston-driven steam pump, a kind of steam engine, John Newcomen, had to cooperate with Savery to implement his idea. Between them, they developed the Newcomen engine of 1712 that could have been used as a prime mover, but was used mainly as an alternative steam-driven pump. The Newcomen engine is known as the "atmospheric engine" because the pressure of the atmosphere provided the actual moving force. Steam was used to fill a cylinder equipped with a piston. The piston was connected to another piston, the latter being part of a piston-pump. When the steam piston had reached one end of its stroke, the cylinder was cooled, the steam condensed, and the atmospheric pressure moved the piston, and the pumping piston with it, to the other end of the stroke. The Newcomen engine was a proper steam engine, as the beam connecting the two pistons might have been used to operate other machinery, but it was mostly used to drive the piston of a water pump. One of the amazing uses for which the pump was sometimes employed was to pump water out of a stream onto a water wheel, with the water wheel operating some machinery, such as textile machines or forge hammers. The intention was to avoid the vagaries of changing water levels in the stream, but the system strikes one as mildly absurd. The advantage was that the Newcomen engine was added to existing machinery and a more dependable operation could thus be achieved without a change in the underlying system. Newcomen engines, with some later improvements by John Smeaton, remained in use for about fifty years.

James Watt is generally regarded as the father of the steam engine that came into general use as the prime mover in all industry for a long period. The steam engine could be used to supply dependable mechanical motion in situations where waterpower was not reliably available and thus made it possible to drive industrial machinery wherever industry found it desirable. The electric motor and the steam turbine began to compete with the steam engine in the late 19th century and eventually rendered it obsolete during the 20th century.

James Watt was a mathematical-instrument maker at Glasgow University and this fact made him into a symbol linking the pre-industrial craft traditions with the scientific foundations of modern engineering. Watt the craftsman and the friend and collaborator of university scientists; Watt the inventor, industrialist and Fellow of the Royal Society (from 1785), forged the symbolic link between craft-based and science-based engineering. One of his friends was Joseph Black, who had established the concept of latent heat[4], and whose knowledge was certainly relevant to Watt's endeavour. While repairing a model of a Newcomen engine in 1764, Watt was struck by its inefficiency. While thinking about the causes of the inefficiency, he became aware of the wastefulness of condensing steam in the cylinder itself and thought that it would be more efficient to have a separate condenser, connected to the cylinder by a system of pipes and valves. The invention of the separate condenser was one of the most important steps on the way to the Watt engine. Using a separate condenser

[4] Latent heat is the energy associated with a change of state, such as from water to steam.

meant that the massive cylinder did not have to be alternately heated and cooled, thus saving a great deal of energy and reducing fuel consumption of the engine by about 75%. Watt took great care to keep the cylinder hot and even surrounded it with a lagged steam jacket. Though the second law of thermodynamics had not been formulated yet, Watt realised that an engine working between a permanently hot reservoir (the cylinder) and a permanently cold reservoir (the condenser) was the most efficient way of constructing a heat engine.

The full theoretical support for this approach was formulated, particularly in the second law of thermodynamics, by several scientists during the 19th century. The best-known contributors to this fundamental law are Sadi Carnot, Rudolf Clausius, William Thomson (later Lord Kelvin), Max Planck and Ludwig Boltzmann. It can be formulated in a variety of ways, but as far as our interests are concerned, the most important formulation, owing to Carnot, says that the efficiency of a heat engine, operating between a hot and a cold reservoir, increases with an increasing difference in the temperatures of the reservoirs. One of the consequences of the second law of thermodynamics is that the construction of a perpetuum mobile, i.e. an engine that produces work without consuming energy, is not possible. Another formulation of the law, owing to Clausius, states that heat cannot travel of itself from a colder body to a hotter body or, in other words, if we wish to transport thermal energy from a cold to a hot body, e.g. in a refrigerator, we must invest energy.

In 1768 Watt entered into partnership with John Roebuck, the Birmingham industrialist and manufacturer of sulphuric acid, who helped him to build the full-scale improved steam engine. In 1769 Watt took out a patent for "A New Invented Method of Lessening the Consumption of Steam and Fuel in Fire Engines." The next few years saw little progress on the fire engine, as he called the steam engine, because Watt had taken up work as a surveyor in Scotland and Roebuck went bankrupt. In 1774 Watt moved to Birmingham and Matthew Boulton, the owner of a small metalworking factory in Soho near Birmingham, took over the business side of the enterprise from Roebuck. His partnership with Watt was one of the most fruitful ones in the history of collaboration between a businessman and an inventor. The first two Boulton and Watt engines were built and installed in 1776, one for pumping water out of a colliery, the other for working the bellows in a metal smelting furnace. In the following five years several engines were installed in Cornwall for pumping water out of copper and tin mines. One of the many problems encountered in the production of steam engines was the boring of sufficiently accurate cylinders that would prevent the escape of steam. The solution lay in the use of a boring machine invented by John Wilkinson for the production of cannon. This is an early example of cross-fertilization – a method from one branch of technology finding a use in a different branch.

Boulton was keen to expand the market for steam engines and thought that this could best be achieved if the engine could drive rotating machinery, such as in textile mills or corn mills. Watt solved the problem of converting the reciprocating motion of the steam engine into rotary motion by the invention of the so-called sun-and-planet gear, suggested by his assistant William Murdock, patented in 1781. He would have used a crankshaft but for the fact that a patent for this had been taken out by one of his assistants and Watt did not wish to be involved either in litigation or the payment of royalties. The sun-and-planet gear served till 1794, when the crankshaft patent expired. Several further improvements perfected the Watt steam engine. The first was replacing the single working stroke by two working strokes, with the steam being introduced on alternate sides of the cylinder, thus avoiding an idle stroke. The second was using the expansive properties of steam by letting it into the cylinder only at the beginning of the stroke. Watt improved the connection between piston rod and beam by introducing a three bar parallel motion arrangement; an invention he was particularly proud of. Next, Watt introduced a flywheel that smoothed out the motion of the engine and, finally, he used a centrifugal governor of his own design, which kept the speed of the engine constant by controlling the amount of steam let into the cylinder. Interestingly, the five hundred or so Boulton and Watt engines that were produced and sold during their partnership, lasting from 1775 to 1800, all operated with low-pressure steam, only a few pounds above atmospheric pressure. Watt was vehemently opposed to raising the pressure because he apparently regarded high pressure and high temperature as too great a hazard. Had he known the second law of thermodynamics, not formulated yet, he would probably have attempted to raise the temperature and pressure of the steam used, regardless of the problems involved.

After the expiry of Watt's master patent and his retirement in 1800, the Watt engine was built by several engineers in Britain, on the Continent and in America. Many further improvements were made over the years.

The drop-valves, for example, were replaced by simpler and lighter sliding valves. Much of the timber used in the construction was replaced by cast or wrought iron. Richard Trevithick increased the pressure of steam up to 10 atmospheres (145 lb/sqin or 10^6 pascal) and Oliver Evans did the same in the United States. They did this without the benefit of knowledge of the second law of thermodynamics, simply because their intuition told them that high pressure would be more effective than low pressure. Trevithick applied his steam engine to a vehicle, building the first steam locomotive in 1804. The locomotive was able to run on a road but not on a cast iron track because the track cracked under the weight of the engine. The road locomotive was ahead of its time and did not prove a success. Another important improvement to the steam engine came when Arthur Woolf patented the high-pressure compound engine in 1804-05. The principle of compounding, originally suggested by Jonathan Hornblower in 1781 but not put into practice because the Watt patent precluded it, consists of using the steam from one cylinder, after it had expanded, as the input into a second cylinder, working at lower pressure. Further cylinders can be added and the principle became particularly effective when high-pressure steam was used to start with. The condenser followed, if at all, only the last cylinder so that, in contrast to early engines, atmospheric pressure did only a minor part of the work of the engine. Further improvements continued and eventually most steam engines disposed of the huge beam and operated with horizontal cylinders instead of the previous vertical ones. They became sleek, smooth and efficient and operated well into the 20th century.

There are two reasons for telling the story of the steam engine in some detail. The first reason is its inherent fascination. So many separate streams of knowledge and experience that came together in a few fertile minds to produce a machine that changed the world. Knowledge of the properties of steam, knowledge about atmospheric pressure, knowledge about the needs of mines and of other machinery, and knowledge about construction materials and their properties all had to come together. Steam power was an essential pre-requisite for the development of a large-scale mass-producing manufacturing industry and a fast high-capacity system of transport. For better or for worse, the world would have been a very different place without it.

Secondly, the steam engine is a prime example of the process of technological innovation, and the case serves us as an illustration from which we can generalize. Innovation occurs when a technological possibility converges with a market opportunity. The several inventors of the steam engine all saw that steam could be used to power a machine that could perform useful tasks, such as pumping water, driving production machinery, powering winding gear and, ultimately, powering vehicles. Their perception of the technical possibilities was closely matched by their perception of market opportunities. There was no need for market assessment or market research; it was obvious for all to see that steam power, with its greater flexibility and independence of location, would supplement and largely supplant the hitherto common waterpower. It was also plain that the use of mechanical machinery, such as the new spinning and weaving machines, would greatly expand. Apart from that, the steam engine created a market for itself in that it increased demand for coal, and thus the need for more water pumping capacity and more winding gear as well as, in later consequence, for more transport facilities provided by steam-ships and railways.

The first models of an entirely new device are invariably somewhat crude when compared to later models. In other words, a new invention undergoes a lengthy process of gradual improvement. Improvement continues from innovation to obsolescence, but is particularly rapid during the early years in the life of a new technology. When comparing a late 19th century steam engine with an early Newcomen engine, we see that the change owed to gradual development was enormous. Many improvements – or even innovations – are achieved by cross-fertilization, i.e. by using a technology from another field and applying it to the new field. The centrifugal governor, or speed regulator, for example, is said by some historians to have been used previously for the control of millstones when Watt adapted it, or perhaps re-invented it, for use in the control of steam engines. Another example, mentioned earlier, is the use of a cannon-boring machine for the production of cylinders for steam engines.

Generally, new technology depends on previously available technology. When the inventor perceives a new technological possibility, he takes into account the manufacturing facilities of the day. Part of the assessment of the feasibility of a new technology is indeed consideration whether it is possible to produce it with known materials and existing machinery. On the other hand, once an innovation comes into use, the facilities for producing it improve at the same time and as part of the development of the innovation. When the first steam engines were manufactured, woodworking facilities, metal pipes, soldering techniques, screws, rivets, metal working facilities, a variety of valves, steam boilers, the production of rope and chains, bronze bearings and a good many other techniques were part of the current technological repertoire and were all used to produce early steam engines. An innovation has to be perceived within the framework of current technological know-how and the successful inventor, in contrast to the writer of science fiction, has to be aware of the limitations imposed upon his imagination by technological reality.

Generally speaking, the mechanical revolution needed to be complemented by an analogous chemical revolution to complete the industrial revolution. By corollary, the new physical sciences needed to be complemented by new chemical sciences. And indeed the old alchemy soon gave way to a new chemistry.

The story of a development as complex as that of modern chemistry is not one with a proper beginning, middle and end. We begin at an arbitrary point in 1661, with an outstanding contribution by Robert Boyle, who pointed out that the elements postulated by Aristotle and the alchemists need not be indivisible and might indeed consist of mixtures of chemical entities. The fundamental laws of the behaviour of gases and their chemical reactions were subsequently established, mainly with contributions from Robert Boyle, Jacques A. Charles (1746-1823) and Joseph-Louis Gay-Lussac (1778-1850). Of equal importance was the gradual establishment of the idea that matter was conserved and could neither be created nor destroyed in chemical reactions. Two of the contributors to this idea were Joseph Black (1728-1799), whom we have met as a friend of James Watt, and Antoine-Laurent Lavoisier (1743-1794). With experiments on combustion and oxidation by Lavoisier and the discovery of oxygen by Joseph Priestley (1733-1804) and, independently and a little earlier, by Carl Wilhelm Scheele (1742-1786), the process of combustion was finally understood and the fanciful old theory of phlogiston was thrown out of the window. Many elements and compounds were discovered in rapid succession and a logical chemical nomenclature, used to this day, was established.

Vague atomic theories of matter were formulated in antiquity, but they had neither predictive nor explanatory value. John Dalton (1766-1844) was the first to formulate the atomic theory of matter in a way that has proved useful and has survived the test of time. When taken in conjunction with the work of Amedeo Avogadro (1776-1856) and others, we obtain a picture of elements consisting of atoms, with the atoms of different elements having different characteristic atomic weights. A number of individual atoms, of the same or several different elements, can combine to form molecules. Thus compounds consist of molecules made up of atoms of the elements forming the compound. This very rough and very brief and very unfair outline, leaving out much important work, shows that by the beginning of the 19th century chemical theory had advanced sufficiently to act as a guide to practical progress. Whereas physics had been short on both theory and experiment until the days of Galileo Galilei, chemistry had gathered plenty of empirical knowledge in the hands of the alchemists, but had been short on useful theory that would enable further progress.

It is not my intention to describe the complete chemical counterpart to the mechanical industrial revolution. I shall give only a brief and incomplete description of some of the important chemical/industrial developments of the time. One such group of chemicals was known as alkali. The term is a little ill defined, but basically it means the soluble hydroxides of the alkali metals (such as sodium and potassium). They are strong bases and are used in a variety of industrial processes, such as the production of paper, glass, soap and others.

Wood was a well-established raw material for the early chemical industry, if that is an appropriate term for the small-scale production of a few industrially useful chemical products. Wood was used to produce tar and pitch for the shipbuilding industry, and wood ash was also an early source of alkali. The production was expensive and soon became unable to supply the increasing demand. The first substitute for wood was seaweed and kelp. The alkali obtained from the incineration of seaweed indeed played an important role in Britain till about 1830. Kelp was not a pure alkali, but it was workable as such and, in later years, it provided a useful source of iodine.

The most attractive raw material for alkali was common salt, but duties on salt in Britain held back development in this direction. The duty on "foul salt" was revoked in 1781 and a number of processes for the manufacture of alkali were patented in the following years and several firms started manufacture. Eventually, the mainstream alkali industry in Europe, including Britain, was founded upon a process invented by the Frenchman

Nicolas Leblanc in 1787. In this process, common salt was decomposed by sulphuric acid, producing sodium sulphate and hydrogen chloride ($2NaCl+H_2SO_4 \rightarrow HCl+Na_2SO_4$). The sodium sulphate was mixed with coal and limestone and heated in a crucible. The resulting ash was leached with water and the soda ash (sodium carbonate, Na_2CO_3) was obtained by evaporation of the water. The process was patented in France in 1791 and Leblanc built a factory for the manufacture of soda ash, but the events of the French Revolution deprived him of both his patron and his factory. In England manufacture of sodium carbonate by the Leblanc process was taken up by James Muspratt in 1823, first in Liverpool, then in Cheshire. Two years later Charles Tennant took up the process in Glasgow. Initially, the gas hydrogen chloride, one of the products of the first stage of the Leblanc process, was allowed to escape through the chimney and caused enormous damage to the environment. There was an outcry against this devastating pollution and a successful demand for intervention by the law. The process was changed and the chlorine was recovered and used to manufacture bleaches in various forms. There was a growing market for bleaches in the textile and paper industries and thus compliance with the social demand to reduce pollution led to profitable new products.

We have seen that sulphuric acid is one of the starting points for the production of soda ash, but it is also the starting point for many other products and processes. Thus the manufacture of sulphuric acid was an important component of the chemical industry. The substance was known to the alchemists and was first manufactured in Germany by two different processes, of which the oxidation of sulphur by heating it with potassium nitrate (KNO_3) in a glass bell was the more successful. As metal workers in Birmingham used sulphuric acid for various purposes, John Roebuck (Watt's later partner) and Samuel Garbett built a plant for its production in Birmingham in 1746. Roebuck, a highly educated and well informed scientist, knew that sulphuric acid does not attack lead and substituted a lead chamber for the glass bell. The substitution of this robust industrial material for fragile laboratory glassware established the basis for the large-scale manufacture of chemicals. Sulphuric acid came to be used as a basic ingredient in bleaching, printing and dyeing processes in the textile, paper and glass industries. Though the production of alkali was the most important market for sulphuric acid up to the first half of the 19th century, this demand was later outstripped by the needs of the chemical fertilizer and other more modern industries, including the manufacture of explosives.

Since the 1780s it was known that the element phosphorus played an important role in plant growth. Guano and bones were imported and ground to provide both nitrogen and phosphorus fertilizers. In about 1840 Justus Liebig, a leading German academic chemist, found that bone meal treated with sulphuric acid was more soluble and therefore more readily absorbed by plants. In 1842 John Bennet Lawes patented the manufacture of the fertilizer "superphosphate" manufactured by treating phosphate rock with sulphuric acid. This was the beginning of the production of chemical fertilizers that rapidly became a large worldwide industry.

The old dyes for textiles, all derived from plant materials, provided a small range of colours and were not colourfast. Synthetic dyes provided a much greater range and better colourfastness. The father of synthetic dyestuffs was August Wilhelm Hofmann who taught in England for a time, before returning to Germany. One of his students, William Henry Perkin, discovered the first synthetic dye, mauveine, in 1856 and began manufacturing it a year later. The German industry, however, with firms such as Badische Anilin & Sodafabrik (BASF) founded in Mannheim in 1865, and with strong theoretical backing from rapidly developing academic organic chemistry, soon reached a virtual monopoly position in the production of a growing range of synthetic dyestuffs. The main raw material for synthetic dyestuffs was coal tar, a by-product of the coke industry that previously had been more of a nuisance than a welcome product. Another German firm, founded for the production of dyestuffs by Friedrich Bayer in 1863, has since become a world-famous name. Bayer was the first who achieved success with the development of synthetic drugs in introducing Aspirin in 1899. By going beyond the period usually regarded as the industrial revolution, extending the discussion briefly to the end of the 19th century, we hope to obtain some valuable insights as this period marks the beginning of organic chemistry.

Apart from the beginning of pharmaceutical research and the production of new therapeutic drugs, the period saw several major breakthroughs in the advance of medicine. The first was the establishment of the theory that the putrefaction of wounds, some diseases, and the fermentation of milk or beer, were all caused by microorganisms. Though there had been previous speculation on these matters, some dating to antiquity, it was Louis Pasteur who finally established the theory and found the means of preventing fermentation by heating (pasteurizing) the milk and thus killing the relevant microorganisms. The process of pasteurization has found widespread industrial application. Advances in organic chemistry brought with them the discovery of antiseptics. The application of antiseptics by surgeons massively reduced the death rate of surgical operations. One of the pioneers of antiseptics was the English physician-surgeon Joseph Lister. Lister used antiseptics for dressing wounds from 1865. The result was that between 1865 and 1869 the mortality in a surgical ward fell from 45% to 15%. Another major benefit of chemical advances was the discovery that certain substances, such as chloroform and ether, could be used as anesthetics. When Queen Victoria accepted chloroform from her doctor John Snow (the same who discovered the cause of cholera) in 1847, the use of anesthetics spread rapidly. Finally, we must mention vaccination. Pasteur himself introduced vaccination against anthrax and rabies. Edward Jenner discovered a method of vaccination against smallpox in 1796 and his method formed the foundation of widespread immunization programmes. The discovery of x-rays by Conrad Wilhelm Röntgen in 1895 completes our highly selective and brutally abridged list of medical breakthroughs between the end of the 18th and 19th centuries. The discovery of x-rays made the body transparent to a certain degree and thereby opened up tremendous diagnostic possibilities. Later it was discovered that irradiation posed severe dangers and, as the reverse side of the same coin, offered therapeutic possibilities against malignant tumours.

We leave the realms of chemistry and medicine and turn to metal-working and machine tools. The successful inventor combines contemporary technological knowledge with imagination and a vision of the technical future. The inventor and/or his business partner also use their imagination to guess the probable market demand for their invention. To bring together a technical idea with possible markets for it, thus realising an innovation, requires knowledge, imagination, faith and perseverance.

The gradual replacement of timber by iron (or other metals) in the construction of machinery was made possible by improvements in the accurate shaping of iron parts. Product innovation often brings in its wake advances in production technology. In modern parlance, product and process innovation are often closely linked. Generally speaking, the change from small-scale individual hand production to large-scale power-driven mass production, brought about by the industrial revolution, required many advances in machine tools. Simple hand tools had to be replaced by machine tools that achieved greater speeds of production, greater accuracy, and greater consistency and uniformity. The accuracy of machine tools makes parts interchangeable and permits the mass assembly of complex artefacts. The 18th and 19th centuries saw the development of a shaper, invented by James Nasmyth, to produce accurate metal surfaces, a milling machine, invented by Eli Whitney (1765-1825), to produce accurate more complex shapes. Whitney invented the milling machine in his bid for the mass production of muskets with interchangeable parts. In a public demonstration reminiscent of Otto von Guericke, he showed that muskets could be assembled by picking parts at random from a pile. Henry Maudsley developed a metalworking lathe from the earlier simple woodcutting lathe, and developed the first screw-cutting lathe. Up to then, screws had been filed by hand and it was neither possible to produce large quantities nor standardized threads. Each individual screw fitted only its own individual nut. From Maudsley's early machine automated screw-cutting machines were developed and standardization was introduced. An early standard, used to this day, was designed by the outstanding toolmaker of his day, Joseph Whitworth (1803-1887), and is named after him. Both Maudsley and his pupil Whitworth produced accurate measuring devices, a precondition for the accurate production of metal parts. All these inventions benefited the development of the steam engine and, of greater importance, were essential for the development of mass production. It would be difficult to overestimate the role of accuracy in mass production. The mass production of accurate parts to be assembled into a finished product forms the basis of all modern production of complex machinery, from the sewing machine to the automobile, and from the gas-turbine to the robot. It was this approach to production that reduced the price and expanded the market for an untold number of machines and devices in modern use.

We should add a brief speculation on the role of patents. Presumably Boulton would not have invested so much capital into Watt's invention had the latter not been protected by patent, and thus showed promise for profit. Too much early competition would have killed the goose that was about to lay the golden egg; it would have deprived Watt of his just deserts. On the other hand, Watt's monopoly slowed down the introduction of some improvements, such as high-pressure compound engines. But did that harm society? I do not think so.

And yet again, the patent protection of the crankshaft spurned Watt on to develop the sun-and-planet gear and thus gave an impetus to a new invention. Perhaps the verdict on the role of patents must be a rather lame "it all depends" on circumstances and on points of view.

After this detour, we shall return to the main inventions of the industrial revolution and briefly mention the development of the steam locomotive, the steam-ship and railways. The story is so well known that extreme brevity will suffice here. The two best-known contributors to these developments are George Stephenson (1781-1848) and Isambard Kingdom Brunel (1806-1859).

Stephenson acquired his knowledge of steam engines when he got a job as an operator of a Newcomen engine working in a coalmine. He rose to a position of chief mechanic in a colliery and had opportunity to see the operation of an early steam traction engine for hauling coal, built by John Blenkinsop. Blenkinsop equipped the wooden track with a toothed third rail and the engine operated by engaging a ratchet wheel with the toothed third rail. Stephenson regarded this unreliable mode of propulsion as unnecessary and designed, in succession, two successful locomotives with smooth driving wheels. The second used part of the steam to increase the draught of the funnel and thus increased the performance of the engine. Trevithick had used a similar system earlier. After building several more locomotives for the colliery, Stephenson managed to convince the promoters of a proposed horse-drawn railway link between Stockton and Darlington in Northern England to try out a steam locomotive. In 1825 the *Locomotion* pulled the first ever passenger train at 15 miles per hour (24km/h). The line was mainly used to carry coal and proved very successful in bringing down the price of coal. Four years later, Stephenson's *Rocket* won, with a speed of 36mph, a competition to build a steam locomotive for a railway line connecting Manchester and Liverpool. Neither Stephenson nor the steam locomotive ever looked back and a veritable railway fever broke out, building railways and all that goes with them all over Britain, the Continent and America. The unstoppable process had its enemies. The main opposition came from farmers, who feared the loss of their markets for oats if steam engines replaced horses. Opposition also came from citizens frightened of the huffing and puffing smoking monsters that moved at unprecedented speeds.

The development of railways had far-reaching social consequences. The capacity for moving goods increased enormously and this was a pre-condition for expanding industry and trade. The mobility of people increased equally enormously, with consequences for trade, for travel and tourism and for city centres. A vast building programme of railway track, railway stations, bridges, rolling stock, locomotives, and hotels was set in motion and the concept of tourism emerged. City centres were in turmoil as stations and hotels were built and track was laid. New occupations came into being, such as engine drivers, firemen, signalmen, stationmasters. Trade and occupations associated with horses and carts became much reduced, while the new occupations rose. It would theoretically be possible to draw up a balance sheet of profits and losses. No accurate assessment is known to me, but general opinion has it that the gains were greater than the losses. Small consolation for the losers. Some losers were among those who had flocked to invest into the new technology. There was much over-investment and many failures, though many a fortune was also made. The phenomenon of over-investment in promising new technologies is a general one. The bursting of the modern 'dot.com' bubble is not dissimilar.

The military potential of the railways for the quick movement of troops, supplies and equipment was soon seized upon. Particularly the continental nations regarded the railways as of too great a strategic significance to be left to private enterprise and the states became heavily involved in the control and ownership of the new system. In Britain, it was left entirely to private enterprise, which resulted in some chaotic development.

Isambard Kingdom Brunel became chief engineer of one of the new railway companies, the Great Western Railway, in 1833. The construction of railway lines involves a great deal of civil engineering, including the building of bridges and tunnels. Brunel made considerable contributions in this field, as well as in the design of railway stations. He was an engineer of remarkable versatility and apart from his contributions to the advancement of railways and of civil engineering, also designed the first ocean-going steamships. Before Brunel, small river steamships had been in operation ever since Robert Fulton, with considerable commercial and political backing, had built the *Clermont* that operated on the Hudson river from 1807 and was followed by a great number of paddle steamers on the great American rivers. The history of this invention is controversial but the controversy is of no great interest to us. The first of Brunel's three ships, the *Great Western,* launched in 1837, had a wooden hull and was propelled by paddle wheels, but also carried sails. It was the first steamship to provide a regular transatlantic service. His next ship, the *Great Britain* (1843), had an iron hull and was the first large ship with a screw propeller invented by John Ericsson. The case of the ship's propeller is interesting from the point of view of historiography. Whereas the Anglo-Saxon histories of technology ascribe the invention in the 1830ies to the Swede Ericsson (and occasionally to the Englishman Francis Smith), German and Austrian historians ascribe the invention to the Austrian forester Josef Ressel and date it to 1827. The final of Brunel's steamships, the *Great Eastern* (1858), carried the principle of "belt and braces" to an extreme. It had a double iron hull, two paddle wheel engines, two propeller engines, as well as six masts rigged with sail. It was originally built for the Eastern Navigation Company to operate on the route to India and was the largest ship in the world; too large for most ports. The ship was sold to different companies and eventually was employed to lay the first successful telegraph cable across the Atlantic, completed in 1874.

Steamships were soon developed, built and operated by a great many companies and came into universal use for the carriage of goods and passengers. The Great Western Steamship Company, owners of the first two of Brunel's ships, was not commercially successful and was soon overtaken by a shipping company founded by Sir Samuel Cunard that became known as the Cunard Line. Competition between British, American, French, German and other shipping lines became fierce. The compound steam engine propelled them at ever increasing speeds. The overall impact of steamships upon world trade cannot be overestimated. World trade grew rapidly and much of this growth was owing to the increased speed and capacity of shipping. After the collapse of the revolutions in Europe in 1848, the desire for emigration to America increased and the steamship made a considerable impact in providing a large capacity for carrying emigrants with great discomfort at the cheapest possible rates. As usual, the old technology fought back and made improvements in an attempt to avoid or delay its demise in the face of the new technology. Sailing vessels improved greatly both in speed and in capacity, culminating in the fast clippers, but were unable to withstand the competition from steam and had virtually disappeared by the end of the 19th century.

A qualitative and quantitative leap in the production of iron and steel is another hallmark of the industrial revolution. Steel became, and has remained, the most important material of human civilization. Machines, machine tools, buildings, means of transport, all this and much else became dependent upon iron and steel. Although we like to think of our present age as the silicon age, in reality steel is still the most important material that sustains our civilization. The first step in raising iron production was made by substituting a plentiful fuel – coal converted to coke – for the increasingly scarce charcoal used hitherto.

Forests are among the first victims of any rising civilization and industrialization.[5] Timber is cut down for building, shipbuilding and construction, as well as for charcoal and for heating and cooking. Forests are cleared for pasture and agriculture. It is not surprising that charcoal was in short supply when increasing demands were made and many forests had disappeared, especially in Britain. One of the properties of technology is to seek solutions to problems such as shortages of certain materials or bottlenecks in certain manufacturing processes or in supplies. As charcoal was becoming scarce and expensive and timber supplies were limited by their very nature, many people tried to substitute plentiful coal for scarce charcoal. Technologists and businessmen are always in search of opportunities and any shortage provides an opportunity. Compared to Britain, it took many more years before charcoal was dispensed with in Germany, because the shortage of charcoal was not as acute.

The revolution in iron production started a little earlier than the mainstream industrial revolution. All iron prior to the 18th century was smelted in furnaces fuelled with charcoal. As charcoal became increasingly scarce and expensive in England, many unsuccessful attempts were made to use plentiful coal instead. Success came in 1709, when Abraham Darby, a cast-iron ware manufacturer in Coalbrookdale (Shropshire, England) succeeded in producing pig iron in a blast furnace fuelled with coke. The advantages of coke are many, quite apart from its cheapness. It is less brittle than charcoal and thus larger furnaces with heavier loads of iron ore and fuel can be built. It also reaches higher temperatures and the iron produced is more fluid and thus Darby's cast-iron products became finer and his business flourished.

5 In O. Rackham, The History of the Countryside, Dent, 1986, it is argued that the destruction of forests is to blame entirely on agriculture and not on industry.

Some of Darby's success was owing to the lucky circumstance that the coal he used had a low sulphur content. In general, coke-smelted cast-iron was not as strong as the charcoal-smelted variety and was not as successfully converted to wrought iron by the traditional method of forging. The problem was caused by the presence of impurities in the coke, particularly sulphur and impurities in the iron ore.

The problem of converting poor quality pig iron into good quality wrought iron was solved by a series of inventions, starting with the so-called puddling process, patented by Henry Cort in 1784. The process essentially consists of stirring molten iron with iron rods and thus bringing the impurities to the surface and continuously removing the surface layer. The process is labour intensive and can only be carried out in batches, but it was successful and was used by a large number of manufacturers all over the world. However, the puddling process was too slow to keep pace with increasing iron production from ever-larger blast furnaces and new methods of producing wrought iron were sought. At this stage we shall introduce the term steel in lieu of wrought iron, as it has become customary to use this term for all iron products with a carbon content below 2%. Iron with higher carbon content is still known as cast iron.

The first converter for the conversion of pig iron into steel by a non-mechanical process was announced by Henry Bessemer in 1856. Several others had similar ideas; particularly William Kelly in the USA had the same idea but could not put it into practice for lack of industrial support. The converter is a large vessel that can be tilted and the essential process consists of blowing air through molten pig iron. The air converts the impurities, especially silicon and manganese into oxides that are removed with the slag. The resulting steel was poured out (cast) and was of better quality than the blooms produced in the puddling process. By sheer luck, the iron used by Bessemer was free of phosphorus and it turned out that this was a condition for the success of the original Bessemer process. The problem of phosphorus was solved in 1875 by Sidney Gilchrist Thomas, who used his considerable knowledge of chemistry to suggest lining the Bessemer converter with a strong basic substance, such as dolomite or burned limestone. This would combine with the phosphorus and could then be removed with the slag. He was granted a patent in 1877 and the combination of a Bessemer converter with the Thomas improvement was highly successful in the production of cast steel.

An alternative conversion method was developed by the brothers Wilhelm (Sir William) and Friedrich Siemens and by Pierre-Émile Martin. The essential feature of the open hearth furnace, developed by Siemens, was to increase the temperature of the blast of air by using a heat exchanger, heating the incoming air by the outgoing flue gases. A patent was granted in 1861 and the open-hearth method became more widespread than the Bessemer process. Martin succeeded in producing better quality steel by using the open-hearth furnace, and adding scrap steel to the pig iron. He too obtained a patent, but was financially ruined by patent litigation while firms using his process made fortunes. The process became known as the Siemens-Martin process and came into very wide use for the production of steel. It was essentially replaced only in the middle of the 20th century by the basic oxygen and other processes.

Between 1838 and 1845 Robert Bunsen, a German university professor famous for his Bunsen burner, examined the efficiency of British and German blast furnaces. He made several suggestions that successfully improved the quality of the pig iron and the thermal efficiency of the furnaces. This is an early example of the collaboration between practical engineering and academic science. Good quality cast iron was of great importance as engine cylinders as well as cannon were manufactured from it. In 1779 Abraham Darby built the first bridge made of cast iron in Coalbrookdale and this was the beginning of the era of iron and steel bridges.

The successful methods introduced in the British iron and steel industry were soon transferred to other industrial countries. John Wilkinson introduced the use of coke for smelting iron in a blast furnace to Le Creusot in France in 1782. He also started the production of armaments there, but the industry began to flourish only when Eugène Schneider and his brother Adolphe bought the works in 1836 and expanded them to become one of the world's top players in steel, shipbuilding, armaments, locomotives and so forth.

The first firm to introduce the Bessemer converter (1862) and the Siemens-Martin open-hearth process (1869) on the European continent was Krupp in Essen. The firm was founded by Friedrich Krupp in 1811 and greatly expanded under the leadership of his son, Alfred Krupp. Krupp produced a large range of steel products, among them the first seamless steel railway tyre. The firm became most famous (or notorious) for their production of cast steel cannon, first shown at the Great Exhibition in London in 1851. By the time of Alfred

Krupp's death in 1887 the firm had supplied artillery pieces to 46 nations and he had acquired the nickname Kanonenkönig (cannon king). On the other hand, Krupp was a paternalistic industrialist who created many welfare facilities for his workers, such as a pension fund, housing, hospitals and schools. By the time of his death the firm had grown from employing 7 workers to a workforce of 21,000. The firm played a major role in World War I with its 420mm howitzers, nicknamed Big Bertha, which, jointly with the Austrian 305mm howitzer built by the Skoda works, destroyed the Belgian fortifications in 1914 and enabled the German army to enter northern France via Belgium. Big Bertha could propel shrapnel weighing nearly a tonne over a distance of about 15 km.

The Skoda works are another example of the new engineering industry expanding throughout Europe and America. Emil Škoda was an engineer who bought a small machine workshop in Plzeň in Bohemia in 1869. The town was then located in the Austro-Hungarian Empire and is known as Pilsen in German. Although the Skoda works achieved great importance, the town's world fame happily rests more on its beer than on it guns. Skoda became a major manufacturer of industrial machinery, locomotives, cars, and arms, including armour plate, heavy artillery and, in 1890, one of the world's first machine guns.

We cannot leave the expanding steel industry without at least a brief mention of steel in the USA. The most outstanding name is Andrew Carnegie (1835-1919). The son of a Scottish hand-weaver impoverished and made rebellious by the mechanical looms and forced to emigrate to America, Carnegie started work as a young boy in menial tasks but rapidly rose through the ranks by virtue of his outstanding talents. Having achieved managerial positions and a great income through shrewd investments, he began to concentrate on steel in about 1872. He founded the J Edgar Thomson Steel Works near Pittsburgh, which later became the Carnegie Steel Company. His company was the first to introduce the Bessemer converter in the USA in 1870 and, some years later, the open-hearth process. Carnegie was a leading light in the drive toward greater efficiency and greater vertical integration of the firm. American steel production exceeded that of Britain from about 1890 and the Carnegie Steel Company was the leading producer. Andrew Carnegie retired in 1901 and devoted his time and money to philantropic activities. The various Carnegie foundations are still among the largest and most active philantropic organizations.

Virtually all land and sea transportation became dependent upon steel. The expanding rail network consumed large quantities of steel and probably could not have expanded unless steel replaced cast iron for rails. Steel replaced timber in the construction of textile machinery and in the construction of the very epitome of the Industrial Revolution, the steam engine. Steel converted these machines from slow moving huffing and puffing monsters into sleek smooth machines. Steel products became specialised according to end use, though surprisingly stainless steel did not become commercially successful till the early 20th century. The ready availability and consistent quality of steel contributed greatly to its extended use in the building and construction industries. Steel and steel reinforced concrete became the major construction materials for bridges, dams, large buildings, including skyscrapers, tunnels, and pipelines. Advances in agricultural machines owed much to improved quality and availability of steel and cast iron. Modern industry is built on a foundation of steel. Silicon has been added as another fundamental material in mid 20th century.

It is not possible to single out some achievements as more fundamental than others, but if I had to choose the four most important technological innovations of the Industrial Revolution, I would select: 1. improvements in the manufacture of iron and steel; 2. the introduction of mechanically operated production machinery; 3. the introduction of the steam engine; 4. the increase in accuracy of machining operations. The most crucial organisational innovation, conditional upon the technological innovations, was, of course, the introduction of the factory system of production with all its far-reaching grave social consequences.

All the major and minor mechanical inventions that added up to the Industrial Revolution were made by skilled craftsmen, not by academically trained engineers or scientists. Men such as James Watt had good knowledge of science, but they were not scientists in the usual sense of the word and had no university training. All the inventions of machine tools were made by skilled mechanics, many of them trained by a single outstanding master toolmaker, Henry Maudslay. The inventions in textile machinery and many innovations in steel production were also owing to master craftsmen or self-taught industrialists. The innovations in chemistry and in medicine, as well as later innovations in heat engines, were introduced by academically trained scientists or medics. It would seem that craft training, coupled with natural intuition and talent, were perfectly capable of making mechanical inventions, whereas intuition fails when it comes to chemistry and the more abstract thinking required for more recent technological innovations.

Unfortunately, advancing technology also led to a revolution in arms production and warfare. Gunpowder, the so-called black powder, is said to have been invented in the 10th century in China and used predominantly for fireworks, though its first military use in a primitive bamboo rocket is said to date to the 13th century. The real origin of black powder is disputed, though why so many nations and people should lay claim to this deadly invention is an enigma. Black powder consists of about 75% saltpetre (KNO_3), 15% charcoal and 10% sulphur. For many civilian applications, such as mining or tunnelling, the potassium nitrate is replaced by sodium nitrate. From about 1862, when Alfred Nobel built a plant for the manufacture of nitroglycerin, black powder was gradually replaced by this new explosive and its various derivatives, including trinitrotoluene (TNT). They came into military use from about 1904.

Firearms in the modern sense seem to have made their first appearance in the 14th century. The musket started life as a muzzle-loading shoulder held firearm evolved from the smaller harquebus in the 16th century in Spain. In the middle of the 19th century it was replaced by a breech-loading rifle. Breech loading is much faster than muzzle loading and the term rifle implies a weapon with a rifled bore, i.e. one with a shallow spiral groove cut inside the barrel. Using an elongated projectile, the groove imparts spin to it, which keeps it on a steady course and thus increases the accuracy of the weapon. The rifle became the dominant infantry weapon and, in advanced and automatic form, is in use to this day.

Breech loading became effective when combined with a cartridge made of brass or similar, containing the projectile, the propellant and a percussion cap. The rifle with bolt action, i.e. a spring-loaded bolt that strikes the percussion cap when the trigger is released, came into universal military use by the end of the 19th century. The battle of Königgrätz (now Hradec Králové in the Czech Republic) between Austria and Prussia in 1866 showed the overwhelming advantage of breech loading. The Prussians had an early version of the breech loading bolt-action rifle, whereas the Austrians were equipped with muzzle loading rifles. The Prussian soldiers could shoot six times in the time taken by the Austrians for a single shot. The Austrians and their Saxon allies lost the battle and the war. Thus a relatively small technological advance changed the course of European history.

The most obvious development owing its advance to better materials, especially to cast steel, was the artillery. Cannons became larger and more robust and their range and accuracy increased greatly. Artillery shells became more sophisticated, heavier and more deadly. From about 1850, rifled gun barrels became standard and this necessitated the use of elongated, rather than round ammunition and much greater accuracy was thus achieved. Shrapnel, invented by the British artillery officer Henry Shrapnel, was introduced in the 1790s. Originally it consisted of a spherical shell packed with black powder and musket balls and equipped with a fuse. It had the effect of deadly musket fire of great intensity over a long range. Shrapnel and fuses for different purposes were developed, such as for use against infantry, or against armour.

With the advent of the railways and various other heavy vehicles able to move artillery pieces, armies became more mobile. With the advent of breech-loading rifles and cannon, their firing power increased greatly and warfare changed from man-to-man combat into a longer-range exchange of deadly fire, with only occasional hand-to-hand combat carried out with bayonets on rifles. Only the cavalry still used lances and sabres, but only till the beginning of the First World War. During that terrible war the face of warfare changed again, as it did in every major war fought since the Industrial Revolution.

We may regard the Industrial Revolution as the period of transition between technology serving human needs and technology creating needs with the intent of making money from the gratification of the needs thus created. Up to the Industrial Revolution technology mainly served real vital needs for food, clothing and shelter and, for the majority of people, not much else. It is true, of course, that ever since the earliest kingdoms technology provided luxuries for the rich, but the majority of the population remained untouched by such riches. It is also true that technology provided the means of warfare since the dawn of humankind and, alas, to this very day. I do not wish to argue that warfare is a real need – quite the contrary it is the greatest curse of humanity and the destroyer of all hope for a world worth living in. However, it appears that war is deeply ingrained in human society. Society without war has remained a dream that lives only in the minds of people without power, in rhetoric, and in fiction. We are forced to the unhappy conclusion that technology, in serving the needs of warfare, is serving a vital need of a sick society. Though perhaps we are letting technology off too lightly. Perhaps part of the blame for warfare falls upon technology and technologists and their unbounded love for the creation of ever-new fearful means of destruction. Technologists are not, of course, the controlling factor. Control is firmly in the hands of the rulers who demand the weaponry and finance its development, purchase and use. Technologists go wherever the jobs are and do whatever the higher authorities, be it management or government, demand of them. Technologists are, nevertheless, guilty of feeding the demand with constantly improved weapons and military equipment. They may only be doing their jobs, but do they not show more enthusiasm than is strictly necessary? Scientists and engineers get carried away and become fascinated by their researches and deadly inventions. The world is a complicated place and even those engineers who might be inherently reluctant to be involved in weapons development are often persuaded by arguments of necessity and by the conviction that they merely help to defend their own people. Nobody acknowledges being the aggressor – everybody is the victim of aggression and persuades engineers and scientists that it is their duty to help defend their country against the attacker. The industrial-military complex, this unholy alliance between arms manufacturers and the military, is alive and well and is still a major force for evil in world politics. They have a very large influence on what technologies shall and shall not be developed.

During the Industrial Revolution technology acquired two new properties that mark its transition from servant of need to servant of greed. The new entrepreneurs were in it for the money. They unashamedly invested in technology for profit and equally unashamedly sought inventions that would multiply their profits. Of course the inventors were in it out of curiosity and regarded the tasks they set themselves as challenges to be overcome. But even the inventors kept at least one eye on profits and their motivation was a mix between engineering and financial challenge. The investors, though fascinated by the new technologies, and thus also motivated with a mix of greed and curiosity, were motivated mainly by the hope of profit.

The second new property of technology was the arousal of new needs. When it became possible to manufacture cotton cloth more cheaply, people bought more cotton cloth in the firm belief that they needed it. When it became possible to travel faster, people, at least those who could afford it, discovered that they were in a great hurry to get to faraway places. When the pendulum clock was invented, people of means found it absolutely necessary to furnish their homes with one or more suitably ornate pendulum clocks. And so forth, the list could be expanded and, with further industrialisation and further inventions, it could be expanded to infinity. In our day it is no longer possible to draw up a finite list of artefacts at our disposal. Yet technology is inventing more and more and economists and politicians call, in rare unison, for accelerated innovation. Not many will argue that these innovations are driven by need, rather than by greed. And yet in the developing world (if indeed it is developing) people are malnourished or starving and are forced to drink unsanitary water that causes disease and death.

We call the Industrial Revolution a transition period, because technology only started on its path of becoming a tool of greed and, arguably, still only provided for needs that were not far removed from being essential. Profligate consumption was about to begin, but had not begun yet. On the other hand, the destruction of the environment began in earnest with the Industrial Revolution. As the consumption of coal for heating and for the production of steel and the generation of steam to power machinery rose, so the output of sulphur dioxide increased and began to destroy forests and buildings. Cities began to be covered in soot, smog, grime and smoke and became places of destruction of buildings, plants and human health. Increasing traffic densities caused congestion, accidents and an appalling stench. The nascent industry regarded the rivers as freely available sewers and it has taken 200 years to clean them to a pre-industrial state.

Living conditions in the densely crowded housing of the new industrial labourers were appalling. Working hours were long, working conditions terrible, disease was rife and life expectancy very low. The introduction of mass production did lower the prices of goods and people could, and did, increase their consumption of manufactured goods, but the benefits of the new productive capacity were unevenly distributed and the effects upon urban amenities, and upon the landscape surrounding urban centres, were devastating. In fact many of the newly created industrial centres show scars of indiscriminate development during the nineteenth century to this day. Derelict land, slag heaps and slum dwellings still disfigure many industrial areas.

As the cities grew and cheap dwellings were erected for the newly arrived industrial workers, problems of sanitation became severe. In London most houses were equipped with cesspits only and these were often allowed to overflow. The overflow was washed into inadequate sewers and ended up in the tidal flow of the river Thames. The sewage was washed up and down the Thames and entered into the drinking water. The result was that the whole of London became extremely smelly – it became known as the Great Stink – and that deadly outbreaks of cholera were frequent. It was believed for a long time that cholera was carried in the stinking air, until Dr John Snow discovered in 1854 that a particular outbreak was associated with drinking water drawn from a particular parish pump. By the middle of the 19th century the houses of the well to do were equipped with some form of privy and these were mostly connected to cesspits and occasionally to sewers. Nevertheless, the custom of collecting night soil in cities continued till the end of the 19th century. The poorer districts had communal privies serving several houses.

Parliament debated the issue of sewage for a long time and eventually allocated a large sum to the Metropolitan Board of Works to build a proper sewerage system. The system was built between 1859 and 1875, under the direction of the chief engineer Sir Joseph Bazalgette, and much of it is operational to this day. The sewers were built of brick and the discharge was carried to the East of London. As the flow was driven by gravity, it reached its destination well below the river and had to be pumped to the level of the river with the aid of steam engines. It was discharged into the Thames at high tide and was swept into the sea by the outgoing tide. The episode of London sewerage demonstrates that private investment, such as in cheap housing, cannot cater for the public good unless forced to do so by suitable regulation. Some form of public intervention is essential if the public interest is to be safeguarded.

Two other developments proved of importance in making life in the new crowded cities more tolerable. In addition to providing sewers, the provision of clean piped water was a major step toward healthier and more comfortable living. The arrangements for the supply of water varied greatly from city to city. In 1848-49 nine different water companies supplied London, supplying a total of about 200 million litres daily. When water was simply drawn from the rivers and the rivers became increasingly polluted with industrial outflows as well as with untreated sewage, the risks of disease increased greatly and aroused public alarm. In 1840 the British Parliament set up a select committee to look into the matter, resulting many years later in the establishment of a Waterworks Clauses Act (1847) and a Public Health Act (1848). By this time the water companies were no longer drawing water from the most polluted parts of rivers. Their supplies consisted of a mixture of water drawn from cleaner parts of rivers, from deep wells, and of water brought in from greater distances. From the beginning of the 19th century water filters gradually came to be used. They consisted of layers of washed gravel and of washed sand. The water passed slowly through the filter that had to be cleaned from time to time. In order to cope with changes in demand and in water levels of the rivers, the water companies or municipalities, as the case might be, started a major programme of building reservoirs. The water from the reservoirs was deemed to be clean. By the middle of the 19th century most urban houses had water piped to them, albeit intermittently, forcing them to have their own cisterns.

It is likely that the combined effect of proper sewerage and clean water contributed as much to public health as all the medical sciences put together. Be this as it may, the 19th century saw a great increase in population. The population of England, Wales and Scotland was 10,500,956 in the first census of 1801. By the census of 1851, the population had almost doubled to 20,816,351. Similar increases occurred in other countries. The main growth occurred in the cities, not so much because of increasing population as because of the continued migration from country to town.

After sewerage and water supplies, lighting was the next most important improvement for city dwellers. Before the advent of electric light, gas lighting provided a very acceptable intermediate solution. Though there were many prior investigations and inventions, the story of gas lighting begins in 1801 with a public demonstration by Philippe Lebon in Paris. Lebon obtained gas by destructive distillation of wood[6] in what he called "thermolamps" and burning the gas to obtain both heat and light. In Britain, the most important investigations into the properties of coal gas and its uses were carried out by a leading engineer of the Boulton & Watt Company,

6 Destructive distillation of wood means heating it in the absence of a supply of air.

William Murdock. In 1792 he produced gas by destructive distillation of coal and used it to light a room. The firm showed little interest in his continuing experiments, until one of Watt's sons alerted them to the possibilities of gas lighting after he had attended the demonstration by Lebon. From 1804 Boulton&Watt sought orders for gas lighting equipment and manufactured it till 1814. Though several gas lighting systems were installed in cotton mills and elsewhere, the business did not fit well into the programme of the successful firm and was abandoned in the face of more successful competition, particularly by Samuel Clegg. Clegg, like Murdock before him, used a cast iron retort to distill the coal but, unlike Murdock, purified the gas by passing it through a lime solution and bubbling it through water, thus eliminating some of the nasty smell of earlier gas. The burners consisted of small nozzles or a narrow slit in a metallic container. Clegg's equipment was installed in cotton mills and other factories and in some large houses.

Despite these modest successes, it was obvious to the entrepreneur Frederic Albert Winsor (a German called Friedrich Albrecht Winzer who came to England in 1803) that producing gas on the spot for each lighting installation was not the way forward. Instead, he suggested producing gas in central generating plant and piping it to consumers. Such enterprise required too much capital to be financed by a single businessman and Winsor tried, with eventual success, to establish a limited company. He found a sufficient number of investors and, in 1812, obtained a charter from Parliament. Previous to the charter he had demonstrated the potential of gas lighting for illuminating streets by installing gaslights in a section of Pall Mall in London in 1807. The company was formed and eventually settled on a new name, The Gas Light and Coke Company. The production of coke and the production of coal gas are much the same process: the destructive distillation of coal. Coal gas consists mostly of hydrogen, methane and carbon monoxide and its production leaves coke and coal tar as by-products. Coke and coal gas were usually produced by the same company in the same plant. After a brief period of erratic management by Winsor, Samuel Clegg joined the company and by the end of 1815, some 26 miles of gas main had been laid in London. The pipes were cast iron, whereas in the USA wooden pipes were used. The connections to the consumers were made with smaller steel pipes that had to be fabricated and welded from strips until some time after the invention of a pipe-drawing process by Cornelius Whitehouse in 1825.

The early lighting was suitable only for large spaces because the combustion of the gas fouled the atmosphere. Matters improved when an atmospheric burner was introduced in about 1840. This had at least two, sometimes three pipes: one for the gas, one for a supply of air, and one for removing the combustion products. Gas lighting became truly competitive with electric lighting when the simple flame was replaced by an incandescent gas-mantle, obtained by surrounding the flame with a fabric soaked in a mixture of rare-earth elements. The device was invented by the Austrian professor of chemistry, Carl Auer von Welsbach, in 1885. In this form gas lighting survived well into the 20^{th} century.

It has been argued that street lighting reduced vice and crime in the cities. On the other hand, it has been argued that the provision of lighting in factories has caused the workforce, including children, to work longer hours. It is very easy to argue that the introduction of new technology caused these social ills. We can indulge in flowery rhetoric claiming that machinery killed innumerable newborn infants in the industrial slums or that murderous machinery enslaved, killed and maimed both child and adult workers. We can draw images of merciless machinery crushing their haggard young victims. In a sense, these arguments are true. But in another sense, it is false to blame machinery for the evils imposed by humans upon their fellow humans.

To manufacture anything at all we need to employ so-called factors of production. We need raw materials, suitable machinery, premises, energy, and so forth. All these are usually subsumed under the term capital. In addition to capital, we need workers – labour - to convert all these inputs into the finished product. The main factors of production are labour and capital and, to some extent, managers are free to choose what mix between these factors they wish to use. There are severe limitations on the choice, but some choice is available. The natural inclination of capitalist owners and their managers is to reduce the labour input as far as possible. Labour is awkward to manage and, more importantly, management wishes to reduce the cost of labour as far as possible. The tendency is to pay the lowest possible wage to the lowest possible number of workers. In the early days of industrialisation the possibilities of reducing the labour input were rather limited because the capabilities of machinery were very limited. The only way to save on labour costs was to pay low wages. The balance between capital and labour has shifted ever since, with machinery becoming more automated and technology developing more and more in the direction of labour saving.

In the days of the Industrial Revolution labour was being forced off the land and thus became freely available for employment in industry. Capital was available because many merchants and other wealthy people had accumulated large amounts of money seeking profitable outlets. Finally, total consumption of manufactured goods was limited by the purchasing power of the population rather than by its willingness to purchase. Markets were not saturated and thus any reduction in price could cause an increase in consumption. The introduction of novel production machinery achieved both increased production and increased productivity. Increased productivity led to a reduction in the price of those items manufactured by the new methods. If everybody can buy as much bread, or meat, or apples or any other food as they are able to eat, then we speak of a saturated market and a reduction in price will make no difference to the amount consumed. Clearly, at the time of the industrial revolution the consumption of items such as cotton cloth was limited by purchasing power rather than by need, and demand rose with decreasing prices.

Thus, at the beginning of the industrial revolution, three essential factors were favourable to increased production: availability of labour, availability of capital, and market demand. Two further factors were needed: availability of useful inventions and of entrepreneurial spirit. The coming together of all these diverse factors created a constellation favourable to the Industrial Revolution.

It needs to be added that the availability of capital is not sufficient; the available capital must be in the hands of people willing to take the risks of starting new enterprises. Similarly, the availability of inventions is not enough if the other conditions for implementing the inventions and turning them into innovations are not fulfilled. An invention is merely an idea; it becomes a technological innovation only if and when it is put to practical use.

The social ills caused by the industrial revolution were owing to the social attitudes of the entrepreneurs. Increasing production and decreasing the prices of items of daily consumption, such as clothing and bedding, are not evil in themselves. Employing surplus labour from agriculture in industrial production is not a social evil either, though whether the growth of cities was desirable is a moot point. What was evil was the fact that working conditions were inhuman because the factory owners were too greedy to pay proper wages and provide better conditions and shorter working hours. What was equally evil was that nobody in power cared about living conditions for the workers or environmental conditions in general. Perhaps it would be too much to expect individual entrepreneurs to be humanitarians under conditions of severe competition. Competition drove wages and prices down and nobody cared that it also drove out all human consideration from the process of industrialisation. But if being humane was too much to ask of the competing individual factory owner, it should have been the business of society as a whole to uphold human values in the face of the brutal onslaught of inhuman technology. When we say society should have taken care of these problems, we inevitably enter the realm of politics. For society as a whole can act only through its governance and the governance of the day was firmly in the hands of the upper classes and these were not interested in anybody's welfare but their own. Looking after the environment to safeguard the planet was not thought of at that time.

The Industrial Revolution was a watershed in the relations between technology and society. The introduction of the factory system of production caused a fundamental change in social relations and caused the production of a large range of products to increase greatly and their prices to fall. As if that were not enough, the Industrial Revolution also changed the status of technology from a provider of necessities to a means of making money. The Industrial Revolution marks the divide between a technology that satisfies needs and a technology that gratifies greed. From the point of view of the consumer, an ever-increasing range of goods on offer aroused needs that did not previously exist. From the point of view of the manufacturer and the technologist, technology provided opportunities for profitable investment and technological innovation expanded these opportunities. The Industrial Revolution started, or reinforced, a trend toward using technology not so much to produce goods that we need, but also as a means of making money out of goods that we can sell despite the fact that they are not strictly needed. Technology thus provides both needs and wants and, occasionally, luxuries as well.

The introduction of certain technologies has some consequences that, in one form or another, are unavoidable and can only be avoided by not using the particular technology. Thus the coal mining industry had to be built up to increase output when the combination of coal-fired boilers and steam power became the prime mover in industrial production. It could have been avoided only if people had been prepared to locate all their productive capacities near suitable sources of waterpower or if people had decided not to use the new production machinery. The former would have meant that only a limited number of production sites would be available and industry could not grow at an appreciable rate. The latter would have meant that industry would hardly have grown at all and that people would have had to forego much of their future consumption of cotton and industrialists, or potential industrialists, would have had to forego most of their future profits. Either of these ways of avoiding industrial growth might seem a good idea to some, but basically humans are greedy and want both more profits and more goods.

If we accept that the total rejection of the new technological possibilities was not a realistic option, we remain with the possibility of using the technology and accepting the unavoidable consequences, but avoiding its most damaging impacts. This certainly was a feasible option and it is a sad reflection upon humankind that it was not used or even seriously considered. Coal mines had to be expanded, but was it necessary to employ child labour or make adult labour work such long hours under the most arduous and dangerous conditions? Migration from villages to industrial centres was unavoidable, but could not the housing provided have been of better quality? The use of land for industrial purposes was necessary, but could not dereliction have been avoided and chimneystacks built sufficiently high to avoid the worst of air pollution? The environment was used as a free for all dump, thus saving direct costs but imposing these costs on the environment and thus on the community at large. From the point of view of the industrialists, the costs were conveniently externalised.

The new machinery, like all major technical change, made a lot of skills redundant. When the new power-driven mechanical looms and spinning machines were introduced, the existing spinners and weavers were, naturally, up in arms. They feared that they would be deprived of their livelihoods by being unable to compete successfully with the more efficient new methods of production. They tried two different ways of resistance. Some became militant and destroyed some new machinery and new factories. They are known as Luddites after their probably mythical leader Ned Ludd. They attacked machines and factories at night, but never attacked people. Only when a factory owner caused the shooting of a band of Luddites, was he murdered in consequence. The movement started in late 1811 and lasted only till 1813, when vicious suppression by the government of Lord Liverpool, including several hangings and transportations, put an end to it. The other path of resistance was no more successful. In a vain attempt to hold their own against the new manufacturers, the established craftsmen accepted lower and lower wages for their work until their meagre earnings became so low that it was impossible for them to continue. The economic case for power looms was not, however, immediately overwhelming and it was not till about 1850 that the handlooms disappeared completely.

To understand the impact of the factory system a little better, we shall briefly follow the sequence of development of textile manufacture. First came the cottage industry, where peasant households produced rough woollen cloth from raw wool to finished cloth. This was largely replaced by the putting-out system, where a merchant bought the raw materials and took them through various stages of manufacture to specialist carders, spinners, weavers, dyers or fullers. The specialist workers were more skilled than their peasant predecessors, but still worked from home and owned their simple machinery. They did not, however, own the materials and did neither buy nor sell but were paid for their labour by the merchant, whether by piece rates or by wages. By the time of the industrial revolution, cotton had replaced wool as the dominant material. The putting-out merchant was a predecessor of the industrial entrepreneur, though his outlay of capital was not nearly as great and neither was the degree of control he exerted over the workforce or the process. The industrial system may, however, be regarded as an extension of the putting-out system. In a sense, it took the putting-out system to its logical conclusion. Instead of taking the raw materials to the various workers in sequence, it concentrated the workers and the sequence of operations in a single place. Instead of using individual small machinery, it concentrated the mechanical process into a sequence of power-driven large mechanical devices. Instead of exerting indirect control over the workers, it took complete direct control over them.

The factory owner is forced to employ a large amount of capital on which he will not make an immediate profit, but which will usually prove profitable in the longer run. He has to deploy hope and faith in addition to money. Whereas the small domestic producer was employed by the putting-out merchant, the latter was not actually on the premises and the worker and his family were in control of their own work schedule and had to deploy their skill and knowledge in the production process; the factory worker was entirely under the control of the managers. The working hours were fixed, the work output and the pace were enforced, the worker had no control over anything and very little skill was demanded. Most of the skill had been incorporated in the design of the machines. Though putting-out required a degree of organisation and exerted a great deal of pressure on the worker, it still left the worker with a degree of discretion and the putting-out merchant with a degree of flexibility. In the factory system, on the other hand, the management had to plan and control every step of the manufacturing process in detail. The flow of materials, from the raw materials and energy supplies right down to the sale of the finished products had to be organised; the machinery had to form a system that had to be maintained in good working order. Workers had to be hired and fired, their wages had to be paid and their work discipline had to be enforced. The worker became a mere cog in a large wheel, his discretion was nil and his previous skills were redundant. The new capitalist became the master of men in ways in which the merchant had not been. The community of industrial workers became the working class, whereas their artisan predecessors had belonged to a class of minor independent producers. The families of textile workers still often combined their industrial work with agricultural activities, as had nearly always been the case in the early cottage industries. The industrial worker under the factory system could not combine his arduous work with any other activity.

Technology creates many problems, but also creates many solutions to the problems it has created. We should modify this statement; it is not technology alone that creates the problems or the solutions, it is the way humans apply technology that is often problematic. Consider the example of the creation of densely populated major industrial cities that were the consequence of the rise of industry. The housing erected for industrial workers was of the lowest possible standard and the highest possible density. Initially, virtually no amenities were provided. No sewerage, no lighting, no running water, no proper toilets, let alone bathrooms. Though the application of new production methods demanded an increase in the working population, it did not directly demand that the new workers had to be accommodated in slum dwellings. In any case, the fact that mass production technologies were introduced was owing to human inclinations of greed, not owing to a technological imperative. However, we must start our chain of argument somewhere, so let us start it with the fact that mass production technology was introduced and that workers had to move from the countryside into industrial areas. Surely housing for them could have been of better quality, less dense, more spacious, with little gardens and with proper sanitation. Street lighting was not invented yet but was introduced rather slowly when it had been invented. Other facilities could have been provided and were not. The sole reason for the creation of appalling slums was the fact that industrial workers were paid low wages and could not afford the cost of higher quality housing, quite apart from probably being overcharged by greedy builders and landlords. The problem of slum housing was thus not created by mass production, but by the fact of low wages. Why wages were low is a moot point. Some argue that there was insufficient productive capacity to pay higher wages that would have meant greater consumption of scarce resources by the workers. Others argue that the low wages were a result of the poor distribution of resources, with the rich consuming more than their fair share and not leaving enough for the poor. We cannot resolve this argument; all we can do is point out that the effects of technology are determined as much by social, economic and political decisions as by the properties of technology.

The density of population in the industrial cities and their lack of proper amenities caused epidemics of cholera and other diseases. The provision of proper sanitation solved these problems relatively quickly. But it is arguable that tuberculosis was also caused by industrialization and the solution of this problem took a very long time. In fact it is not completely solved to this very day. The problems created, at least indirectly, by the application of mass production technologies were alleviated by the application of further technologies. Eventually sewerage was introduced, clean water was piped into houses, gas lighting was provided, toilets were improved, and the streets were paved. Technology, as applied by human society, creates problems; technology often can, if society so wishes, solve or alleviate the problems it created.

The problem of obsolescence of skills was in part alleviated by the demand for new skills. Weavers, spinners, dyers, and fullers became obsolete as their crafts were taken over by machines and methods of mass production. On the other hand, some skills were demanded in the design, production and maintenance of the new machinery and in the development of new processes. New skilled occupations, such as boilermakers, engine drivers, toolmakers and mechanics, were created. We do not know the numerical balance between skills lost and skills created, but we do know that for those craftsmen who lost the opportunity to earn their living by exercising their skill the change was catastrophic. We do know that the number of unskilled workers in the factories, who worked long hours under dreadful conditions, far exceeded the number of skilled workers. We do not know whether the new industrial workers were better or worse off when they exchanged their existence as agricultural labourers for an existence of factory workers. We do know that the change was irreversible. The factories were there to stay and the work in agriculture was gone forever. Technological change traps societies into new situations that can be changed only with the introduction of the next generation of technology or by strong political will and action. The third law of technological change[7] states that such change is mostly irreversible. Though this is not a law of nature, it is nevertheless inescapable.

The newly grown cities, and particularly London, became desperately congested, especially during the period when railroads and sewers were built simultaneously. Horse drawn traffic congested the streets and infested the air. Horse drawn traffic also caused quite a few deaths; the traffic accident is as old as wheeled traffic. The motorcar was hailed as the solution to the dirt and smell and congestion. It has not brought about any solution at all, perhaps the contrary. Technology, unwisely used, cannot solve the problems of previous technology, perhaps equally unwisely used.

Before the industrial revolution, society was largely rural and cities were small. Production was entirely in the hands of artisans working in small workshops. Total consumption of energy and material goods was small. At the end of the industrial revolution, society was industrial. Cities had grown enormously, populations had grown, and large numbers of people worked in large factories. Total consumption of energy and of material goods had increased hugely.

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[7] For a summary of the fundamental laws of technological change see ch.7.