Chapter 2

The Metal Ages

Conventionally, the end of the Neolithic age marks the beginning of the Copper Age, which was the early stage of the Bronze Age and this, in due course, gave way to the Iron Age. For our purpose it is important to understand why, and how, these materials, that gave the ages their names, came to replace stone - and each other - as the principal raw materials for the manufacture of tools, weapons and other artefacts. And, of equal importance, we need to understand how the new technologies related to the substantially altered societies of the metal ages. It was a period that saw the rise of the first so-called civilizations, with their great cities, elaborate social organizations, hierarchies, written documents, and, last but not least, organised armies. Technology began to be used – or abused – to enable societies to go well beyond mere survival and to seek grandeur, conquest, wealth and power.

By the late Neolithic, humans had developed quite sophisticated technologies and, more important, had become keen observers of nature, as witnessed by their agriculture and by their art. The small isolated groups of early Stone Age people had developed into societies. Population density had increased and humans had become largely sedentary, thus establishing close contacts within large groups of people. External contacts were assured by widespread trade and by regional centres of congregation.

The pre-condition for these developments was the establishment of an efficient agriculture, able to feed those who worked in it and producing a surplus to feed those who worked in other occupations. Agriculture thus enabled a society to become stratified in terms of occupations and, of equal importance, in terms of wealth and power. Whereas ownership of land means nothing to hunters and gatherers, the ownership of land became significant with the introduction of agriculture. With the concept of ownership, the twin concepts of wealth and inequality acquired meaning for the first time in history. Leadership might have been meaningful in a society of hunters and gatherers and the rudiments of a division of labour emerged in the late Neolithic. However, an extensive division of labour and social inequalities occurred only in association with advanced agriculture and with real wealth.

Apart from wealth through ownership of land, it gradually became possible during the late Neolithic, and more particularly during the metal ages, to acquire wealth in several other ways. First, directly connected to agriculture, it was possible to accumulate not only land but also farm animals and, at various unhappy stages of history, slaves. Secondly, it became possible to accumulate various artefacts, particularly ornaments. As is the case today, skilfully crafted ornaments, whether or not they are made of precious metals or precious stones, can represent very substantial wealth. Finally, as the construction of buildings advanced and it became feasible to build larger and better equipped and ornamented buildings, the ownership of such buildings, from the simple dwelling house to the luxurious palace, represented wealth.

In general terms, technology created surpluses beyond the immediate essential needs of society and such surpluses could be accumulated in a variety of forms to represent wealth. If the accumulation was unevenly distributed among members of a society, then inequality of wealth arose and an intimate connection between power and wealth was soon established. If we define society simply as a large group of people living in a locality and linked through relationships of work, division of labour, family ties, rules of conduct, and administrative or power structures, then we may say that by the beginning of the metal ages simple societies had become established in many localities. Indeed even in the Neolithic rudimentary forms of society had come into being, sufficiently well organised to construct large civic works that represented substantial communal wealth.

The establishment of society is a pre-condition for rapid advances in knowledge and, thus, in technology. For only society can assure that knowledge is preserved and transmitted. Individuals, even the most talented individuals, discover very little for themselves; their knowledge consists mainly of what they learn from the experience of others. This is why we say that knowledge is social knowledge; society is the keeper of knowledge and knowledge is transmitted from one generation to the next within society.

Modern societies take elaborate care of their knowledge. They have large education systems designed to transmit knowledge systematically to the young generation, and they have many other institutions designed to preserve, increase and transmit knowledge throughout society. These include research institutes and learned societies, libraries, journals and books, and much else besides. But knowledge also spreads via newspapers and other media and by word of mouth. Each of us knows vastly more than he or she discovered directly from experiment or observation. Ancient societies had no organisation designed specifically to enhance and transmit knowledge, but knowledge was nevertheless imparted by parents and elders to the young and spread by word of mouth among adults. The more contact there was between people, the more cooperation between craftsmen and explorers, the more trade with distant communities, the more readily knowledge was accumulated, preserved and transmitted. Without such mechanisms complex technologies, such as the smelting and working of metals, could not have developed and spread.

After countless millennia of social development and development of artefacts made of stone, bone, antlers, leather and wood, not to mention ceramics, humans were ready for experimentation[1] with new materials. Late Stone Age humans examined, and experimented with, all kinds of materials they found in nature. Some of the stones they examined behaved in rather strange ways, very different from ordinary stones that they knew so well. When they found small nuggets of gold, silver or copper, they noticed that these 'stones' did not shatter when hit hard, but changed their shape instead. It became apparent that these materials are malleable, i.e. they can be hammered into desired shapes. Although native copper - copper occurring in nature in pure form - is quite rare, it was found in sufficient quantities to learn how to shape it into useful, or merely attractive, objects. Copper can be hammered into a desired shape, but as its deformation progresses, its malleability decreases. The material becomes progressively harder as it is worked; a phenomenon known as work hardening. Work hardening gives copper the advantage that reasonably hard cutting tools, such as sickles or daggers, can be made from it. On the other hand, continued hammering deforms the material progressively less. This must have baffled early workers, but they found a way out of the problem. If the work-hardened material is heated and cooled, preferably rapidly by quenching in cold water, it becomes malleable again. How this was discovered can only be conjectured. I suppose that people knew that hot copper was soft and assumed that it was worth trying to heat hard copper in the hope that it would turn soft, which it did. That rapid cooling enhances this process of annealing is an added bonus, probably discovered by somebody too impatient to wait for the hot copper to cool down naturally. A suitable sequence of work hardening and annealing makes it possible to produce many desirable copper objects. However, because native copper is rare, it was initially used mainly for the manufacture of precious ornaments and jewellery. The oldest such objects were found in Anatolia and date to about 6,000 BC. The oldest copper weapons and implements were found in Egyptian tombs and date to about 5,000 BC. Silver and gold were also used for the production of jewellery and ornaments from about the same time as copper.

In principle, metals differ from rocks in several important respects. Metals are malleable, meaning that they yield and change their shape under an applied force, such as hammer blows, whereas rocks shatter without having changed their shape. Thus metals can be shaped by the application of force without fracturing them, whereas stones can only be shaped by fracture or grinding. If a metal is subjected to a progressively increasing force, say in a press, it will first deform elastically, which means that it will regain its initial shape when the force is removed. If the force is increased beyond a certain value, the so-called elastic limit, the metal deforms plasti-

[1] We use the word experiment with two somewhat different meanings. When speaking of experiment in ancient times and in some contexts, we mean trial and error. When speaking of experiment in the context of science, we mean scientific experiment.

cally, i.e. permanently. Elastic deformation is useful for the production of springs, and also helps when metals are used to bear loads or blows. Metal implements have a toughness that cannot be matched by implements made of brittle materials. The exact relationship between applied force and deformation of metals was not discovered and formulated till the 1660 by Robert Hooke (1635-1703). Metal technology thrived for two thousand years without a proper theoretical understanding of most of its fundamental properties. Metals generally melt at a lower temperature than stones or ceramics and this circumstance makes it possible to cast metals into desired shapes in moulds made of fired clay. Metal casting was developed quite early in the metal ages and has never ceased to be of crucial importance.

The fact that fundamental knowledge about properties of metals was not discovered till the 17th century need not surprise us. The very idea to explore properties, and seek relationships between facts, did not occur to humans till about the 17th century, with a few exceptions in classical Greece and elsewhere. It is said that Galileo Galilei (1564–1642) was the father of experimental science, whereas men such as René Descartes (1596–1650) and Francis Bacon (1561–1626) laid the philosophical foundations to what we know as scientific method, meaning the quest to interpret natural phenomena on the basis of observation, experiment and rational logical thought instead of on speculation, tradition and theological dogma. Observation of natural phenomena, particularly in astronomy, and their rational interpretation by men such as Nicolaus Copernicus (1473–1543, led to early conflict between science and the Church. By the time Johann Kepler (1571–1630) formulated his mathematical laws for planetary orbits, based on painstaking observations by himself and Tycho Brahe (1546–1601), the Church had more or less come to terms with modern astronomy and the idea that the Earth revolves round the Sun and is not the stationary centre of the Universe[2].

We distinguish between scientific observation and experiment. Observation, coupled with trial and error, led to all early technologies. Particularly agriculture owes its existence to careful observations of nature. Many believe that the siting and construction of megalithic monuments, such as Stonehenge, were based on observations of solar phenomena. Observation, aided by early scientific instruments, led to the first scientific breakthroughs in astronomy and other sciences.

The crucial difference between observation and experiment is that experiment deliberately sets out to test various properties of nature by systematic observations of phenomena deliberately set up. Although some scientific instruments, such as the telescope[3] or the microscope[4] were used for making more accurate observations, later instruments were designed and used for scientific experimentation. In modern times these instruments range from the colossal and ultra-expensive particle accelerators used for experimental observations of fundamental particles; to the huge telescopes and space probes used to observe astronomical and astrophysical phenomena; to quite simple laboratory equipment such as scales, optical microscopes, or distilling apparatus. Many of the scientific instruments have become machines in their own right. We thus use accelerators in medicine, speedometers in cars, and computers for anything and everything.

To establish what now seems to us a simple law, known as Hooke's law stating that strain is proportional to stress, or that metals deform in proportion to the force applied to them, required a great deal of painstaking experimentation. First a specimen of metal had to be prepared, say a round rod, with precisely known dimensions, then a force had to be applied to it, say by clamping one end and hanging weights on the other end, finally the extension of the metallic specimen had to be measured as the load was increased. The procedure had to be repeated many times with the same metal and same kind of specimen, then with different metals, different shapes of specimen and different loads. Not only was the proportionality of stress and strain established, but the elastic limit for different metals was measured as well. No wonder it took till the 17th century to hit upon the idea that useful facts could be gleaned only by experiment, as opposed to trial and error or mere observation. When we consider the complexity of scientific investigation and the amount of effort required to obtain some theoretical knowledge, it should not surprise us that people were unwilling for a long

[2] For popular descriptions of the war between scientific and religious astronomy see e.g. Dava Sobel, Galileo's Daughter, (1999) or Arthur Koestler, The Sleepwalkers, (1959). For a philosophical treatise see e.g. Thomas Kuhn, The Copernican Revolution, (1957).

[3] Developed and used by Isaac Newton and Johannes Kepler for astronomical observations

[4] Developed and used by Antonie van Leeuwenhoek (1632-1723) for microbiological observations

time to spend so much effort to no apparent practical gain. It required a mental sea change before purely scientific experimentation became thinkable and desirable. In ancient Greece science, such as it was, was part of contemplative philosophy. Native copper is too rare to serve as a major engineering material. Much more copious supplies of the metal had to be obtained before its use could become widespread. The discovery of copper ores and the possibility of smelting copper from the ore by heating it in an intense charcoal fire took a very long time, perhaps a thousand years. The relationship between knowledge about native copper and the discovery of smelting copper ores[5] is obscure. My own feeling is that as a result of the success obtained with firing clay and thus obtaining ceramics, people began experimenting with heating all kinds of natural materials. Copper ores are rather brittle rocks, useless for the production of tools, but this did not mean that heating them might not yield interesting results. After all, unfired clay is not a very exciting material either. Before smelting became a practical proposition, clay and ceramics for the construction of furnaces and crucibles had to be available. The availability of ceramic materials was one of the necessary pre-conditions for the smelting of metals. It goes without saying that the discovery of the process of manufacturing charcoal was another pre-condition. Wood-fires cannot reach the temperatures required for smelting. When experiments with heating certain rocks (ores) yielded copper, this was probably recognized as the material already known to be useful and the technique of copper smelting was further developed. It took a great deal of further development by trial and error before the process of smelting was perfected and reasonably pure molten copper was obtained. It is not very likely that the discovery of copper as a material for the manufacture of artefacts was the result of a systematic search for a material that could overcome recognised weaknesses of stone and other known materials. It is much more likely that the introduction of copper was the result of a general quest for practical and useful knowledge, and of fun with experimentation, that had already succeeded in producing ceramics. I think that the discovery of copper and its properties resulted from general exploration, from a quest for greater knowledge of natural materials, though not a systematic exploration that arose with the introduction of science many centuries later. The practical utility of copper was recognised only after some of its properties had been explored and understood.

It is now customary to argue at length about whether a technological innovation resulted from an invention that eventually found a market, so-called technology push, or whether it resulted from a known market demand which technologists were able to satisfy with some novel technology. The distinction contains a grain of truth, but is not very helpful. I think such debates are pretty sterile even under modern circumstances and rather inappropriate for prehistory or ancient history. It is true that some technologies were developed as direct responses and solutions to practical problems. The plough or the wheeled cart are cases in point. Other technologies were developed as a result of general exploration and were found to be useful. Needs in those remote days were so great that it is difficult to think of useless technologies that might have been discovered. It is not very important to distinguish between technologies that were triggered by need and those that were triggered by curiosity; all technologies in those days served very real needs.

The period we are speaking of is one in which technology invariably served needs. The days of technology serving greed were yet far in the future. We might regard two types of technologies as possible exceptions: the technology of warfare and the development of luxury items. Sadly, warfare was perceived as a real need and, even more sadly, this is still very much the case today. Luxury items, such as jewellery, catered for the greed of a very small group of the wealthy and powerful classes. Indeed luxury consumption has always been one of the hallmarks of the wealthy, thus distinguishing them from the rest of humanity.

Technological innovation occurs if a technological possibility is found to be of some practical utility. In other words, technological innovation is the result of the confluence of technological possibility and market demand. The debate about which comes first does not shed much light on the process. In the very early historical periods that we are discussing here, needs were so great and so manifold that it would have been unthinkable for a technology to be other than driven by need. We have earlier established a kind of hierarchy of needs. Top of the list are the vital needs of survival, i.e. food, water, shelter, protection against inclement

5 Generally speaking ores are mixtures of compounds containing a reasonable amount of the metal in question, such as oxides and sulfides.

weather and predators. The next level of needs are social needs, i.e. needs of social organisation, of assembly and of ritual. These needs arose as early as in neolithic times and found a technological embodiment in the megalithic monuments discussed earlier. In larger and more complex societies, such as in cities, the needs also become more complex, both in terms of housing, of communication, of water supply, of sewage and garbage removal and, last but not least, of food storage and of administration. These needs did not arise till the rise of the first civilizations. With further increases in hierarchical structures and inequality of wealth, the rich required palaces and ornaments. As skills in pottery developed we find some pottery used as ornaments. As skills in metalworking developed, we find that metals, especially precious metals, were increasingly used for the production of ornaments such as jewellery and ornamented weapons. With the development of long-range trade, precious stones, spices and scents arrived on the market and the rich developed an appetite for such luxuries. Technology began to serve the need of the rich for luxuries and thus began to serve greed as well as need. The greed was that of the rich and mighty, not yet the greed of the technologists or the masses, though traders and jewellers profited from the trend.

There was no general cry for new materials; society did not demand metals. Metals were discovered and their practical potential was realised. The considerable amount of exploration and experimentation necessary for the practical application of metal technology required a considerable amount of manpower. There must have been a sufficient number of knowledgeable and skilful people who were able to spend sufficient time and resources on exploration. There must also have been a reservoir of manpower capable of receiving, applying and further developing new knowledge and new skills. Early hunters and gatherers simply could not have spared the manpower for such enterprise. Late Neolithic society had created sufficient surpluses to make such enterprise possible and society had become sufficiently interconnected to provide the cooperation needed for such development.

When copper had become widely available, it became possible to produce reasonably sharp copper blades for sickles and other cutting tools or daggers. Copper proved useful for cutting tools because it was tougher than stone, though not as sharp. Undoubtedly the first call on the new material, especially when it was still very scarce, was the production of ornaments for the ruling classes and the production of arms. Once copper became more abundant, it was found that hammering a copper sheet into a hollow mould could produce copper vessels, to supplement containers made of ceramic, woven baskets or gourds.

There was a lot to be done before copper could become ubiquitous. The ores had to be identified and mined. Charcoal in sufficient quantities had to be produced. Furnaces for the smelting of copper had to be developed. The ore had to be washed to rid it of earthy material mixed with it and then the ore had to be heated to dry it and get rid of some impurities, such as sulphur. The properties of malleability, work hardening and annealing had to be explored and mastered before copper could be effectively shaped into useful objects. Crucibles and moulds had to be developed for the production of cast copper objects. It is clear that the widespread use of copper was dependent on the development of a whole technological system involving much knowledge. This is an early example illustrating the fact that as technology advances, we increasingly have to deal with technological systems, rather than with individual technologies. Several separate techniques and methods become interdependent to form a complex system. It is the system that performs the task, or satisfies the need. We shall meet this phenomenon many more times. The development of the system that might be called copper technology took a long time and it was not till about 3,000 BC that the use of copper became widespread in the Middle East and started to penetrate into Europe. Whereas the production of a stone tool required no more than two stones and a skilled pair of hands, the production of a metal tool required a whole system of interlinked technologies. And, as mentioned earlier, before the system could develop, some pre-conditions had to be met. It is common for the development of a technology to depend upon the existence of other, earlier, technologies.

Although copper proved useful for the production of sheet material and shapes and vessels that could be made from it, it was not hard enough to be truly superior to flint or obsidian for the production of cutting tools. It was superior only in so far as it could be shaped more easily into more complex shapes. Its softness could be overcome by work hardening, and so copper proved useful, but had no overwhelming advantage over stone in cutting tool applications. The widespread use of copper for the production of tools and weapons occurred only when it was found that a small addition of tin produced a superior material – bronze. We do not know what led to the discovery of bronze. Presumably as part of the process of exploration some other ore, tin ore in particular, was added to the copper ore before smelting and the product proved very superior and was further developed. On the other hand, it may have happened through accidental contamination that was reproduced when its benefits came to light.

With the discovery of bronze, a material became available that was hard and strong and could easily be cast or cold-worked into many desired shapes. By varying the amount of tin added to copper, bronze of different qualities could be obtained. The most common bronze in antiquity contained about 10% of tin. The possibilities and techniques of shaping bronze by hammering (cold working) are similar to those of copper. The superior strength of bronze makes it possible to cast very large objects. Hammering can produce strong and sharp work-hardened blades. As bronze is very much stronger and harder than copper, and is shaped nearly as easily, it proved a truly superior material. Thus the Bronze Age was born and bronze spread rapidly from Egypt during the second millennium BC. It arrived in Western Europe in about 2,000 BC and in Britain and Scandinavia about 100 years later. Despite the late arrival of the Bronze Age in Britain, Cornwall, with its large deposits of tin, was destined to play an important role in it. Bronze was particularly suited for the production of daggers and lance tips, but also for the production of chisels. If we consider that almost all the marvellous temples, pyramids and sculptures of old Egypt were produced with bronze as the only material available for the production of stonemason's tools, we must marvel at the amazing skills and ingenuity these craftsmen could muster.

Pure, or nearly pure, iron occurs in nature in the form of meteorites. Meteorites were explored and used almost as early as native copper, but because of their rarity, their use never went beyond the realm of ornaments. The smelting of iron was discovered much later than that of copper. The reason for the delay is easy to see. The smelting of iron ores requires a much higher temperature than the smelting of copper. To achieve such high temperatures, a lot of development of furnace technology was required, including the use of bellows to increase the flow of air through the furnace. The earliest extraction of iron from an ore dates to roughly 2,000 BC and is thought to have started in Anatolia and Persia, where the smelting of copper was well established.

Smelting was achieved by adding iron ore to a bed of red-hot charcoal in either a bowl furnace or a shaft furnace. The bowl furnace, which did not remain in use for very long, was constructed by digging a hole in the ground and blowing air into it through a pipe. The shaft furnace was built of stone above ground. Natural draft was usually supplemented by the use of bellows made of leather. Early furnaces were not capable of achieving temperatures higher than about 1,150°C and the iron obtained from them was a hot semi-solid lump, known as a bloom, rather than liquid iron. The bloom was then re-heated in a furnace and hammered – forged – while red-hot. The forging expelled trapped slag and charcoal and produced the desired shape. This type of iron is known as wrought iron and was the preferred form in the Iron Age. Cast iron, which contains more carbon and is rather brittle, was used to any extent only in China.

The design of furnaces gradually improved and they increased in size, but remained essentially unchanged till about the 15th century A.D. The usual gradual development to larger size and greater efficiency took place. The larger later furnaces had water-driven bellows and the molten slag would run off into pits. The increasing size of blooms is another case in point showing the tendency for a figure of performance to increase over time. Early blooms weighed only about 5kg, whereas by the 15th century blooms weighing over 100kg could be produced in a single firing.

Iron was a truly superior material. Very much stronger and more ductile than bronze, and easily forged into many shapes, iron served well as a universal material for the manufacture of virtually all tools and weapons and many other implements. The only drawback of iron is its vulnerability to rust. This is a great disadvantage that haunts us to this day, but the advantages of iron far outweighed the disadvantages. In effect, the Iron Age began in about 1,200 BC in the Middle East and south-eastern Europe. It became established in the rest of Europe by about 1,000 BC and in China by about 600 BC. Although the knowledge initially diffused from Anatolia and Persia, it soon acquired regional characteristics by local modifications in many localities. We have said that copper technology has to be regarded as a technological system. The same has to be said, with even greater validity, for iron technology, which forms an even more complex system. One of the components of these systems is a body of expertise, experts in identifying and mining metal ores, experts in smelting, and experts in forging iron tools. The trades of miner, iron smelter and blacksmith were born.

Unfortunately, one of the great “advances” of the Iron Age was the production of swords. Stone is obviously unsuitable for such large blades and even bronze swords would be either too heavy or, if light and slender, not strong enough. It is a sad commentary upon human nature that the sword was hailed as the greatest invention of the Iron Age. Some smiths devised a method of obtaining even harder iron – a sort of steel – for the use in blades, especially swords and knives. They heated the almost finished article in a bed of charcoal. Some carbon diffused into the surface layers of the iron and thus converted these into steel. When the hot blade was rapidly quenched, the surface became hardened. It could be further forged and suitably heat-treated (tempered) to give a hard, sharp, yet flexible blade. The best steels during the Roman period came from India, where small blocks of proper steel – not just surface-hardened iron - were produced in crucibles and sold into Europe and the Middle East.

In a very real sense, the Iron Age never ended, for steel is still one of the most important materials used in our society. The dawning of a new technological age does not necessarily imply the demise of the previous technology. Despite to-day’s importance of plastics or silicon, steel is still very much with us[6].

Apart from metals, the last few millennia of the pre-Christian period produced many further important technological advances. It would not serve my purpose to describe them in detail, or even to enumerate them all. Instead, I shall briefly discuss those that I regard as most important for my purpose of relating technological advances to social change.

Agricultural production required permanent settlements. Perhaps it is more accurate to say that agricultural production and permanent settlements were dependent upon each other. It is not possible to roam the countryside and have fields and paddocks – these are mutually exclusive ways of life. On the other hand, it is impossible to have permanent settlements and rely on hunting and gathering for food supplies. As soon as permanent settlements were required, ways of building permanent abodes had to be devised. Hunters and gatherers could rely on caves for the winter and temporary flimsy shelters for their wanderings; sedentary populations had to build houses that could withstand the vagaries of the climate. There were not enough caves in the right places, nor many caves large enough to accommodate a whole settlement. Thus buildings were constructed with locally available materials and according to local climatic conditions. Timber was often used, but in places where timber was scarce, stone served as a building material. Some dwellings were half dug into the earth, thus probably offering better protection from wind. Roofs could be covered with reeds, straw, hides, or sods of grass. Houses could be square or round, large or small, with internal divisions or without. All houses had fireplaces and often storage places and stone or timber beds were built in. As settlements grew, lanes had to be constructed between houses. Building techniques advanced continuously and it became possible to build larger buildings of better quality. Only in later times and in larger settlements is there evidence of some form of drainage.

Civil engineering made major strides. Canals were built to transport water over quite long distances to feed irrigation systems. Pipes were made from copper or lead and used to bring water into houses. Even rudimentary sewage systems were built. Elaborate water storage systems were devised and dams were built both for storing water and for controlling floods. Simple roads were constructed and streets were built in settlements. Large settlements acquired defensive walls. Fortresses were built and, as a counterpart, complex machinery for the assault on walls and fortifications.

The horse and the donkey were domesticated and mules were added to the range of domesticated animals suited to be used for riding and as pack animals and, later, for drawing carts or ploughs. The obvious advantage of this form of transportation is that it does not have to rely on any form of road. For the transportation of heavy goods over short distances some form of sledge, the so-called travois, could be used. This consisted of a couple of beams connected by a platform and could be pulled by oxen. Friction was obviously rather great and loads had to be kept low. The obvious thing to do was to put a couple of wheels at the points of contact between the sledge and the earth. But how obvious was this?

The wheel is often regarded as the greatest invention of all time, though it would seem that it was invented many times in different places. One can imagine that when the going got heavy, people would put tree-trunks

6 See e.g. Arthur Street and William Alexander, Metals in the Service of Man, 1994

under a sledge to reduce friction and get it moving. From the idea of putting loose rollers underneath that had to be brought forward again and again as the vehicle progressed, the idea of attaching something equivalent to a tree trunk might have occurred to many people. Curiously, the earliest known wheels were not simply disks cut off a tree-trunk but were fabricated from three shaped planks clamped together. The wheel had to be attached to an axle and the axle had to rest in a bearing of some sort. Perhaps the really great invention is the bearing, rather than the wheel. For what use is a wheel without a method of attaching it to a platform or frame in such a way that it could carry the load and yet rotate freely? As a minimum, two holes had to be made in vertical surfaces that were part of the vehicle and a fixed axle with a wheel firmly attached to it at each end had to be constructed and inserted in the two holes. In this construction the axle rotated in bearings attached to the cart. Thus the two-wheeled cart was invented and it was a small step from there to a four-wheeled cart for heavier loads. This sounds simple, but it is not. To drive a cart with four wheels round a curve means that the outer wheels have to cover a greater distance than the inner wheels and also that the front wheels have to be pushed sideways into the curve unless they can change their direction, i.e. unless the axle can pivot round a central vertical axis. It was only when each wheel could turn independently on a fixed axle, and the front axle could rotate round a vertical axis, that a truly driveable vehicle was obtained. The road to this development was a long one.

The ancient technique of rolling heavy loads on tree trunks, always placing at the front the one that came out at the end, was a precursor to the wheel. The main difference consists of the fact that the wheel is attached to the load-bearing vehicle, whereas the rollers are not. Solid wheels fabricated by joining together flat planks of wood and shaping them into a circle probably proved stronger than mere disks cut from tree-trunks and avoided the limitations in size that a tree-trunk imposed. However, solid wheels were heavy and this problem of weight was only solved when the spoked wheel was invented around 2000 BC. The production of a spoked wheel is an altogether more complex proposition that required a good deal of development work. The art of the wheelwright came into being.

A large part of the effort of the draught animal was wasted on friction in bearings and friction of the wheels on the road surface. Friction between a dry wooden bearing and a dry wooden axle is great. This problem was eventually solved by producing wheels with iron hubs that turned on a solid axle, either of wood or of iron, and using lubricants to reduce friction further. The spoked wheels were equipped with iron tires, consisting of an iron hoop slipped over the rim of the wheel when hot. On cooling, the iron hoop contracted and held the wheel firmly together. Thus the tire strengthened the wheel and also reduced friction between the wheel and the road surface.

The harnessing of the power of the animal to the cart poses its own difficulties. With oxen, a yoke can be attached to the horns or to the withers of the animal. With horses or donkeys the matter is more complex. They have no horns and the withers are not suitable for holding a yoke. For several centuries a strap was put round the chest of the animal and attached to the cart. This had the severe disadvantage that the strap could slide up and press on the animal's windpipe, thus reducing its traction effort considerably. Gradually the harness was improved by holding it firmly in place so that it could not press on the windpipe, but for heavy loads and heavy horses the solution came only with the invention of the rigid collar, which allowed the horse to exert its full strength in traction. The rigid horse collar is reputed to have been invented in China and did not come into general use in Europe till medieval times.

Why did this development take several centuries? There probably are two parts to the explanation. First, it may have taken a long time to diagnose the problem. It was probably not at all obvious that the horses could have developed greater strength but for the foolish method of harnessing them. And even once the cause was suspected or discovered, the method of solving the problem was by no means obvious. It took a long time to realise that there was a problem, and a further period to find suitable solutions. In this case, the technological innovation was truly driven by a need.

There is plenty of evidence that considerable knowledge of farm animals had been accumulated by the time of the Iron Age. Farm animals were improved by selective breeding and, if the oxen used as draught animals were indeed oxen and not bulls or cows, then castration must also have been invented during this period. This means that the role of testicles in determining a male animal's temperament, as well as its reproductive capacity, had been recognised and acted upon. These discoveries are far from obvious and required powers of observation and abstraction, as well as curiosity and patient experimentation.

It is said that the horse was first domesticated in the middle Dnieper region in the middle of the fifth millennium BC.[7] This seems likely, for the steppe of that region is the place where horses could best develop their potential for speed and strength. Riding in a forest does not bring nearly as much advantage as riding in a steppe. This is a case when natural circumstances caused development to move in a certain direction. The same region also produced covered wagons with solid wooden wheels in the third millennium BC.

Topography and climate and other external environmental circumstances do, of necessity, influence technological developments. It is well known, for example, that the Aztecs, with all their sophistication and their wheeled clay figurines, never developed the wheeled vehicle. Presumably it would have been pretty useless in their mountainous environment and, if that were not enough reason, they had no large domesticated animals that could have been used for drawing such vehicles[8].

The wheel was useful not only for transport but also for the manufacture of pottery - the potter's wheel; for spinning - the spinning wheel; and, in somewhat different form, for grinding grains - the quern. It is perfectly possible that any of these four applications was at the root of the invention in any particular locality and the other applications followed from what we might call cross-fertilisation. An idea that is successful for a particular application can be transferred with relative ease to other applications. It requires the ability to recognise some basic principle – in this case rotary motion – and to grasp that this same principle might be useful for a variety of purposes. Cross-fertilisation, or the transfer of ideas from one sphere to others, always has been one of the ways in which inventions have been made.

I think that as far as transport is concerned, the wheel was a result of experimentation aimed at solving problems arising out of the need to transport heavy goods, such as stones, carcasses, and timber. In its initial stages of development the cart did not prove so very successful because a cart without a road is not very useful for carrying loads. Roads were needed to complete the system of wheeled transportation. The invention of the wheeled vehicle, as so many inventions, found an early application in warfare with the development of a light fighting vehicle; the chariot. Ceremonial types of wheeled vehicles have been found in burial chambers, showing that this technology was used in ceremonial from very early days.

Need was the original driving force that created technology during the early millennia of human existence. Gradually technology became emancipated in the sense that it became able to offer products and processes that were not strictly needed. Technology became able to offer wares that, if all went well, aroused the desire to buy and use them. The offer – an invention – became an innovation if, and only if, some people agreed to use it. Thus invention, need and desire became inextricably bound into a bundle that we call, for the sake of brevity, technological innovation. The inventor changed his/her question from "how can I solve this problem" to the question "if I produce this product, will anybody regard it as useful". A technological innovation occurs if a constellation of technical and socio-economic circumstances is favourable to it.

Innovation in the military field is a somewhat special case because the military are particularly receptive to innovation. Anything that promises to kill enemies more effectively, with less effort and less danger to the own side, is welcome. Anything that promises to protect the own side more effectively from the enemy is equally welcome and the same is true for anything that makes fortifications more effective or, on the other hand, promises to destroy enemy fortifications more efficiently. It should not surprise us that as soon as metals had been discovered and techniques for producing and working them had been developed, metals were employed for the manufacture of arms and armaments. It should not surprise us that as soon as wheeled vehicles were invented a fighting vehicle was developed and as soon as the horse had been tamed it was employed in warfare, both for drawing chariots and for riding. As soon as the bridle, the saddle and, first and foremost the stirrup had been invented, a revolutionary new type of mobile fighting force – the cavalry – came into being and was not replaced till the early 20th century.

7 Felipe Fernández-Armesto, Civilizations, (2000), p.113
8 George Basalla, The Evolution of Technology, (1988),pp. 7–11

In heavily wooded or steep terrain both cart and chariot were useless until the time when proper roads were built. Only the open steppe permitted their widespread use and indeed it was from such steppes in Central Asia and the Middle East that chariots and carts originated round about 3,000 BC. The chariot became a mighty fighting machine. It was the military applications that proved the strongest incentive for making the vehicle lighter, faster and more manoeuvrable. Once the chariot was adopted as a weapon, the improvements were obviously called for and may be regarded as social needs that technology was called upon to satisfy. The interplay between technology and need is complex and the lead role may change in the course of a technological development. Sometimes technology leads and offers solutions to problems yet to be articulated, and sometimes a need is articulated and sets a goal for technology to achieve.

The plough is a good case in point. From the beginnings of cultivation, it was recognised that soil had to be loosened and weeds had to be suppressed to create the right conditions for successful sowing. Even before cultivation, edible roots had to be dug up. Both operations could be carried out with a variety of hoes, or with digging sticks. The digging stick could be branched and, sometimes, weighted with a stone. In this form it could be pulled along the field and thus became the forerunner of the plough. In its simplest form and application, a human did the pulling. The digging stick became a plough by the addition of a somewhat broader and harder share, initially of bronze and later of iron. When the stick was replaced by a frame that could be attached to an ox or another draught animal, the transformation to a simple plough was complete. Many more refinements followed over the centuries. The share became bigger, the frame stronger, wood was often replaced by iron. Great improvements came when a so-called moldboard was added that made sure that the plough not only loosened the soil, but also turned it over and thus buried stubble and weeds. Much later, wheels were added that made the work of pulling the plough much less arduous.

One has to suppose that the digging stick and the hoe were invented to answer the immediate needs of digging up edible roots. When the possibilities of cultivation were discovered, these implements were put to the new tasks of loosening the soil and weeding. As plots grew larger, and cultivation more widespread, people began to look for more efficient methods of cultivation and the plough emerged from these attempts to speed up and ease the work to be done. Particularly heavier soils could not be worked without a strong share, a strong frame, and an animal to pull the plough. It is not surprising that heavier soils in the north came under cultivation much later than the lighter soils around the Mediterranean and Middle East. By the stage the plough had developed, a new weak link emerged: friction between the plough and the soil made it hard to pull and this effort was wasted. At this stage the idea of attaching wheels emerged, presumably by cross-fertilisation from wheeled carts and chariots. At each stage of development a new weak link was discovered and remedied. The earliest forms of plough came into use by the end of the fourth millennium BC. Some authors claim that the wheeled plough was invented by the time of the birth of Christ, but others dispute this and think it was much later.

The plough is a good example of a sequence of events that, over the course of time, lead from a simple and rather ineffectual technology to a more complex and more effective one. Improvements are made as weaknesses of a technology are discovered. There is interplay between a need and a technology. The technology improves as it attempts to satisfy the need more effectively. There often comes a stage, however, when the technology leaps ahead of the need and causes all kinds of social change. The plough continued to get bigger until, when the tractor had been invented, it reached a size when only a powerful tractor could draw it. By this stage it had become extremely expensive and extremely efficient, making it necessary to invest much capital and shed much labour. Capital and energy intensive agriculture with very high labour efficiency emerged, and caused all the well-known social and ecological consequences. Technology pushed far ahead of basic need, probably ahead of any reasonable need, and caused as many problems as it solved. This may be a moot point, but it is beyond dispute that advanced agricultural technology is a major cause of social and ecological changes – for good or for ill, probably mostly for ill. Should development have stopped at some stage? Who was to say when? When is a technology good enough to satisfy a need and when does it overshoot the mark and begins to cause more problems than it is worth? These are difficult questions to which there is no general answer. It seems to me that development should stop if it is about to cause adverse environmental effects, and/or if it is likely to cause major adverse disruptions to the social system. When ploughs and tractors became too expensive for small farmers, and when it became apparent that agriculture would have to shed a major part of its labour force, and that the heavy machinery was damaging the soil, and that agricultural surpluses would be produced, it probably would have been time to call a halt to further technical development. This can be seen with hindsight. The real question is whether it could have been foreseen and, if so, whether development could have been halted, and by whom. Generally speaking, it never is possible to halt a technological development that offers substantial benefits to the most influential groups in society.

The dawning of the metal ages marked the beginning of what is known as the early civilizations. Several large cities grew and became the hubs of powerful states. During the fourth millennium BC, civilizations arose mainly along and around river valleys, presumably because of the availability of water for irrigation in these semi-arid regions. The rivers Jordan, Tigris and Euphrates in the Middle East, the river Indus in what are now India and Pakistan, the river Nile in Egypt, and the Huang-Ho river valley in China became centres of civilizations. The first of these civilizations, the Sumerians in southern Mesopotamia, built large cities such as Ur and Lagash. The Babylonian and Assyrian civilizations followed the Sumerians and built cities such as Babylon and Nineveh. The Egyptians had Memphis and Thebes, while the Indus civilization was centred on Harappa and Mahenjo-daro. We shall take a slightly closer look at these civilizations in the next chapter.

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