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The Nature of Engineering

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The Nature of Engineering

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Preface

This essay is a contribution to the current debate about the impact of technology on our lives, the ethical problems arising therefrom, and the ways in which society can exercise control. In a democracy, such control is unlikely to be effective unless the public, Civil Service and politicians have a clear idea as to the nature of engineering and the conditions under which technologies develop and make their impact.

In recent years engineering students have been encouraged to think about these matters by the requirements for membership of the Council of Engineering Institutions. All universities and polytechnics include a subject called 'The Engineer in Society' in their degree courses. It is hoped that this book will be found useful as supplementary reading for these students.

The book contrasts the history of technology with that of science and attempts to highlight the essential features of technology in relation to other forms of knowledge. For this reason it has been subtitled 'A Philosophy of Technology'. The reasons why engineering spawns ethical problems in this century are examined, and the pros and cons of advanced technology vis-&-vis 'alternative' technology are discussed. The book concludes with a description of recent views on decision-making in the technological sphere.

I am most grateful to colleagues with whom I have discussed parts of the book, and in particular to my wife and David Blockley who have been kind enough to read the complete manuscript and make helpful suggestions. Gillian Davis deserves a special mention for her skill at deciphering my appalling handwriting and for her efficient typing.

<div align="right">G.F.C. Rogers, 1982</div>

Chapter 1

Introduction

We live in an age of the specialist: an age in which specialised activity is pursued by specialists for the applause of specialists. Even within each relatively narrow branch of knowledge, whether it be English literature, Christian theology, physical science or mechanical engineering, the specialists can seldom talk meaningfully to one another. The Anglo-Saxon scholar has just as much difficulty in communicating with the critic of the modern novel as the thermodynamicist has in conveying his ideas to the stress analyst. It is not a matter of 'two cultures' but of a myriad of cultures, all of which are incomprehensible to the majority of mankind.

While no one can hope to understand the work of more than a few of these specialists, many of us can and should try to understand the framework of ideas within which each broad group operates. This is especially necessary when the specialists are engineers or technologists because their power to influence the way in which we live has reached an awesome level. Within three decades they have made available nuclear energy, space exploration, world-wide television via satellites, the microchip and robotics, and now there is the prospect of genetic manipulation. Finding ways of harnessing the power of technology for the greater benefit of mankind, and of moderating the social stresses arising from the ever-increasing rate of technological change, poses unparalleled problems for humanity. There is little hope of accomplishing either of these things unless both the public and government understand the nature of engineering and the ways in which technologies are born and develop.

Before proceeding, it is necessary to say something about the distinction between 'engineer' and 'technologist'. 'Engineer' is derived from the Latin *ingeniatorem* meaning one who is ingenious at devising. It was originally used to refer to those who specialised in the construction of military equipment and fortifications, and in the early days there was no clear distinction between engineer and architect. We will use the term engineer in the modern sense as being a professional man with sufficient theoretical knowledge and practical experience to enable him to take responsibility for technical projects and be a driving force for technical innovation. This is how the term is used on the continent of Europe. It is usual to indicate the broad field of endeavour within which the engineer works by adding such adjectives as civil, mechanical, electrical, aeronautical, chemical, and so on. The professional institutions are also categorised in this way. We shall ignore the loose usage in the U.K. where 'engineer' has a much wider connotation: from a semi-skilled machinist to a chief designer; from John Smith on the shop floor or the railways to Sir Frank Whittle who fathered the jet engine and Lord Hinton who organised the construction of our first nuclear power stations.

An engineer in the professional sense needs not only an adequate knowledge of technical matters, but also some familiarity with aspects of economics, accountancy and law, together with considerable organisational ability. Indeed, if he is running a small consultancy practice – in structural engineering say the economic and legal aspects are central to the conduct of his business. The technical matters of which an engineer should have cognisance comprise the 'technology' of his sphere of activity. It follows that the engineer is a somewhat broader individual than the technologist. An engineer in charge of the whole or part of a project may use the services of a number of different types of technologist just as he will use the services of many types of craftsman.

In one sense, however, the term 'technology' may seem broader than 'engineering'. This is because there are technologies which do not fall within the well-known categories of engineering. These are associated with what are called the process industries: paper-making, food processing, drug manufacture and so on. The word 'technology' has its roots in the Greek 'techne' meaning art or skill and 'logia' meaning science

or study. The term is therefore normally applied to any area of study which has a scientific component but which also includes a body of practical knowledge not yet susceptible to theoretical analysis. In colloquial language, a technology always contains a strong element of 'know-how'. Using technology as a collective noun, we may take it to mean the study and reasoned account of technical processes. The essential feature of such processes is that they enable man to transform the physical world around himself. He does it by:

(a) increasing the *efficiency of his body* via tools covering the whole spectrum from small hand tools to automatic machine tools, by giving it mobility through transport systems, and by housing it in greater comfort than nature provides;

(b) increasing the *efficiency of his senses* via instruments which enable repeatable measurements to be made and which amplify sight and sound or measure phenomena not directly perceivable by the senses; and`

(c) increasing the *efficiency of his intellect* via aids to memory, intelligence and communication such as printing, photography, computing machines and telecommunication systems.

This book is an attempt to make explicit the main ways in which engineering knowledge differs from other branches of knowledge, and we shall be concentrating mainly on the technical aspects of an engineer's task. For this particular purpose, therefore, there is no reason to treat engineer and technologist as other than synonymous terms. Much of what is said will in any case apply also to technologies which fall outside engineering. When discussing other aspects of an engineer's work, such as his role as decision-maker, we shall use the term more precisely. The book has been sub-titled 'A Philosophy of Technology' and we must now briefly consider the sense in which we are using the term 'philosophy'.

One of the distinguishing characteristics of *homo sapiens* is his extraordinary ability to reflect upon what he is doing and to derive considerable pleasure and satisfaction in the process. Philosophy is the name given to the process of reflecting upon an intellectual activity, when the process is carried out in a reasonably systematic manner. The philosophy of a branch of knowledge, such as religion, history, art or science, is normally an attempt to understand the principles of the mode of thinking involved and to see how that branch fits into the whole corpus of human knowledge: Part of the pleasure derived comes from the feeling of security that the possession of a map always gives whether it is a geographical map or a map of knowledge. To understand the principles of a mode of thought, we have to clarify and organise the general concepts used in that mode. Ordinary language is vague and imprecise; as indeed it must be to encompass the tremendous range and variety of human experience. When selecting and focusing on particular cross-sections of experience, however, we are able to develop sharper and more precise tools of expression by distinguishing clearly the different meanings that a word has in different contexts. Another part of the pleasurable feeling comes from the higher level of understanding that this affords, and the intellectual excitement of discovering hidden presuppositions of which one was previously unaware. . This can lead one to suppose that by philosophising about a subject one might be able to pursue the subject itself more effectively afterwards.

Certainly a clear idea as to the status of engineering knowledge and the place of engineering in society is necessary for those who allocate research funds and who have to decide between the competing claims of engineering and science. It might help governments also, in their difficult task of deciding which of several major technical projects to support. Lastly, it might encourage enterprising youth to see engineering as a career of vital importance to the well-being of society.

When approaching the philosophy of technology, the first question which springs to mind is why is there so much philosophy of science and so little philosophy of technology? Philosophers have always hoped that the philosophy of science might in some way help scientists to improve their performance. It may be that philosophers have been discouraged from examining technology by the feeling that engineers are less likely to take note of their efforts because engineers have a practical end in view and are less concerned with theoretical understanding for its own sake than the scientist.

Perhaps another reason for the neglect of technology by philosophers can be found in the following aphorism:

> A scientist looks at the world and tries to explain what he sees: an engineer looks at the world and tries to supply what he sees is missing.

Like all dichotomies, this presents a very simplistic view of the true state of affairs. Scientists play a large part in changing the face of the world, and engineers often try to explain phenomena. In practice, therefore,

there is no clear distinction of this kind between the roles of the scientist and engineer. If we substitute 'science' for 'a scientist' and 'technology' for 'an engineer' the aphorism might have a grain of truth. This overcomes the difficulty that sometimes scientists act as engineers and vice versa.

The thought behind the aphorism does explain why philosophers have paid much more attention to science than to technology or engineering. For many centuries science has been a recognised body of thought with its own methods for acquiring knowledge and establishing the truth of its propositions. These methods, and the presuppositions behind them, have thrown up problems which are of obvious interest to philosophers. What are the implications of science for the theory of knowledge (epistemology)? What is the nature of scientific explanation, and how does it differ from other varieties such as historical explanation? What is the logical status of scientific laws and scientific proof? Are scientific propositions capable of proof or are they merely falsifiable statements? And so on.

The aphorism also explains why philosophers seldom seem to use examples from scientific activity when tackling problems of moral philosophy or ethics: if science is simply concerned with explaining nature explaining what exists ethical problems do not arise. Scientists themselves, however, have been very concerned with ethical problems because of course science is inextricably linked with engineering whose *raison d'etre* is 'supplying what is missing' and thereby changing the way in which we live. Medical science generally, and genetics in particular, are rife with ethical problems at the present time. This is because they are essentially practical sciences whose application has obvious social consequences involving consideration of human values.

One may agree then that it is natural for philosophers to have become interested in science. Perhaps our aphorism also suggests reasons why there has been no corresponding interest in technology. If technology is merely concerned with the arbitrary production of artefacts, as and when an engineer sees something 'is missing', it can hardly throw up interesting philosophical questions. Certainly it poses psychological problems – for example, the origin and nature of invention and creativity – but perhaps not strictly philosophical problems. However, if the fundamental purpose of technology is to change the way in which we live – whether because it changes the means of producing ordinary goods (replacing humans by machines) or because it introduces novel goods with far-reaching social consequences (the motor car) – surely it should at least throw up ethical problems of interest to philosophers. One obvious problem is the relationship between collective ethics and personal ethics. Technology provides a rich source of examples of collective ethical problems, if by collective ethics we mean the moral stance adopted by a society. For example, how should a wealthy society view the maintenance of resources for future generations, its effect on the environment, risk and the value of an individual's life, or the problems of the developing countries? It is the increasing power of technology, making it possible for us to regulate events which hitherto were regarded fatalistically, which throws up these ethical problems. Whatever else it contains, any philosophy of technology must surely concern itself with ethics.

But of course technology does not merely involve the arbitrary production of artefacts: of little more than toys to keep modern man from worrying about the cosmic questions 'Who are we?', 'Why are we here?' and 'What should we do?'. Viewed from the stone age onwards, technology has played an important role in the development of man as a species and it is a vital part of our cultural heritage. Moreover, technology is not just a matter of invention and manipulative skill: it is something more than craft. The development of abstract concepts plays an essential part, and in sophisticated engineering there is a vast theoretical content. It can be argued that the type of reasoning involved must be distinguishable from that used in science, if only because of its direct connection with purposive design and development. There is certainly a task for a philosophy of engineering or technology here, in delineating such distinctions.

Some of the questions that might be raised are as follows. What is the relation between technological rule and scientific law? What is the logical basis of validation by practice and how is this related to the idea that scientific statements are falsifiable rather than verifiable? Is there a logical difference between scientific prediction and technological forecast? Does the way in which technologies are classified differ significantly from the way the sciences are classified? How do the presuppositions which foster the development of technology differ from those which foster the growth of science? Is there an historical contingency about technology not present with science in that technologies are superseded in rather different ways than are scientific theories?

It seems clear then that a reasonable first step in placing technology correctly within the corpus of human knowledge is to examine the precise nature of the distinctions that can be drawn between science and technology. We know that science and technology are now very closely linked: man could not have set foot on the moon without making full use of both forms of knowledge. Many modern technologies are based

on scientific discoveries and all make use of science to some degree; while science makes a correspondingly great use of technology to provide its complex research equipment. Perhaps we can obtain a clearer view of the distinction by going back in history to a time when this close link was not in evidence. In doing so it is easy to jump to the conclusion that technology predated science and that it provided an essential stimulus for the growth of science. But are we sure that we are still speaking of the field of thought and activity which we now categorise as technological? Or might we be thinking of something which was no more than invention (often as a result of some lucky combination of circumstances) coupled with manipulative skill, that is, craft. Such a combination was no doubt the precursor of technology just as classification of natural phenomena was a precursor of science. If it should appear that what can properly be called technology did not materialise until craft began to be combined with science, the historical approach may not contribute much to our search for distinguishing features. Nevertheless, by telling us something about the precursors of science and technology the historical approach may carry us a step forward. Chapter 2 will be devoted to this topic.

The questions posed earlier, concerning possible philosophical points of difference between science and technology, will be taken up in chapter 3. Furthermore, because we are interested in placing technology correctly within the complete spectrum of human knowledge we shall also from time to time be referring to knowledge which is other than scientific or technological. In chapter 4 we take up the question of creativity in engineering and examine the processes involved in engineering design. Ethical problems raised by technological developments, and the current controversy between advanced technology and alternate technology, receive attention in chapter 5. Finally, in chapter 5 we discuss matters relating to decision-making in the technological sphere and the ways in which society can exercise control. In these last two chapters, and in the summing-up, we shall be dealing with human values and ideas about which there is a wide variety of opinion. Inevitably at this stage we shall be thinking of 'philosophy' in the colloquial sense, as when people refer to their 'philosophy of life'.

Chapter 2

The History of Technology and Science

Craft 10 000 BC to AD 500; natural philosophy 3000 BC to AD 1400; science 1400 to 1700; technics 500 to 1850; science 1700 to 1850; development of engineering education; some characteristics of science and technology.

From recent archaeological evidence it appears that man has been using tools for at least two and a half million years. For most of this period, however, he had to be content with stone clubs and axes and simple tools of bone and antler. Progress seems to have awaited the last of the major climatic changes, around 10 000 BC, when the ice sheets began to retreat in the northern hemisphere. This is a suitable starting point for our history because then man began to change from a hunter/gatherer to a farmer/shepherd. He found that the better grains could be cultivated, and that some animals would breed in captivity and so could be domesticated. This transition involved a change in man's attitude to his environment from something given, to something which could be controlled and modified: and this must surely be the fundamental presupposition upon which all technology is based.

In saying this we are not suggesting that technology appeared on the scene at this early stage in man's development. As our story unfolds it will be clear that the gestation period was very long, and even longer than that for science. What we find ourselves describing first is the growth of *craft*, until a turning point is reached around AD 500. We follow this with a description of the development of what was called *natural philosophy* during an overlapping period from 3000 BC to AD 1400. We shall argue that what can properly be called science arose in about AD 1400 and we shall continue that story up to AD 1700. We then revert to AD 500, to rejoin the history of craft, only to find that it is now more appropriately called *technics*. We carry this story through to 1850, by which time we shall find that *technology* proper has arrived. Finally, we revert to the history of science and continue it to the same date. A final section provides a brief review of the history of engineering education.

By the end of this historical survey we shall have a clearer idea of the distinctions between craft, technics, technology, natural philosophy and science. Historians generally, and archaeologists in particular, tend to use the term 'technology' very loosely. It is as well to remember that if we have different words in the language, which superficially seem to mean the same thing, there are probably subtle differences of meaning which are worth retaining.

Craft 10 000 BC to AD 500

A suitable location to have in mind for the start of this history is the Middle East. Firstly, in this region there was a happy combination of fertile slopes and valleys for food production, mountain ranges rich in minerals, and rivers leading to the Mediterranean and Indian Ocean to aid communication. Secondly, archaeologists have probably been more active in this region than in any other. And thirdly, the development of our western civilisation and culture had its origin in this area.

Once farming had become an established way of life, there was a need to store grain and the craft of making fired clay pots was eventually established. This led to what was virtually a 'cottage industry' turning out a variety of fired clay articles from pots – utilitarian, ceremonial and decorative – to building bricks. Time and again we see that a craft is invented to meet a precise and perceived need although, once invented, other needs which can be served by that craft soon spring into existence. It is this interaction between need,

invention, and the creation of new needs which is responsible for the exponential expansion of crafts and ultimately of technology. Other techniques, for milling grain, spinning thread and weaving reeds, were also developed during this early period.

When the technique for making bronze was established in about 3500 BC, all this activity could be pursued more effectively with better tools, and specialisation of labour became the norm. Progress was made in building, and towns began to appear in which men could come together to cross-fertilise their crafts and hand on their skills more easily to the next generation. At this time arose some remarkable men, many of whom can only be described as engineer/architect/priests. They were capable of organising the construction of such monumental achievements as the Karnak temple, the pyramids, and complex irrigation schemes. By 2000 BC some of the towns had become cities and the centres of small empires. The introduction of iron as a tool and weapon material in about 1400 BC (perhaps by the Hittites in Central Turkey or their near neighbours) added impetus to these developments, as did the growth of shipping for the exchange of raw material and finished products. By 700 BC countries were minting coins to facilitate trade.

Of course the transition from hunter to farmer to city dweller took place in other parts of the world also, and similar crafts were developed in these other regions more or less simultaneously. What differences there were, depended very largely on the type of raw material available. For example, whereas iron was wrought by hammering in the Middle East, it was more often cast in China. This was probably because Chinese iron ore had a higher phosphorus content which gave the metal a lower melting point. Not surprisingly, the craft of mould-making reached a higher standard in China than elsewhere.

In other regions, the transition from hunter went no further than primitive farming, forms of which still exist today in South America and New Guinea. The question arises as to why further advances were made in some areas and not others. We shall never know, for example, whether the process of annealing metal was discovered purely by a chance observation when a piece of copper fell accidentally into a fire, or whether some logical process of thought was involved. What is certain is that only in areas with good communications could such discoveries spread from one community to another and germinate. And only in fertile areas could some of the people be freed from food production to be enabled to live in cities and devote their time to the development of crafts. Such conditions existed pre-eminently in the Middle East, but were clearly lacking in the Amazonian basin.

Continuing our historical excursion, the period 1000 to 300 BC saw a wealth of invention, particularly in Greece. The welding of iron by hammering, the potters wheel, lathes, clocks, pumps – all these processes or devices and many more seem to have been invented in this period. The waterwheel, which one might regard as the first device for harnessing the forces of nature to supplement human and animal power, was probably invented in Northern Greece. No doubt an important spur for these developments was the rather higher status which was accorded to craftsmen by the Greeks than by the Asiatics. We may note, however, that the inventions were still based on simple principles, for example, that air expands on heating, and used relatively simple components such as springs, screws, pulleys, levers, cogs and cams.

Around 300 BC the centre of power shifted to Rome. The Romans brought a variety of crafts to a new pitch of perfection, but curiously enough invented few new ones. For example, although not the inventors of the waterwheel, the Romans improved it by mounting the wheel vertically and using gears to increase the speed of the millstone. Furthermore, they carried the idea with them throughout their Empire, and so were responsible for the spread of this valuable source of power. It has been argued that the lack of technical progress played a part in the decline of the Roman Empire. Some historians have suggested that there was a lack of incentive owing to the widespread use of slave labour, and that an excess of manpower led provincial rulers to discourage anything that might cause unemployment and social unrest. According to Suetonius, the Emperor Vespasian (AD 69-79) was generous to an inventor who proposed a device for transporting heavy columns to the Capitol, but made no use of it saying 'You must let me feed my poor commons'. Other historians have argued that the low level of technical knowledge possessed by the administrators and civil servants was an important cause of stagnation. Both these reasons have an uncomfortably familiar ring in the 1980s.

What the Romans did – apart from giving the world a sophisticated legal and administrative system – was to invent the professions of civil and military engineer. These were men who designed and planned projects which could be carried out by the lower orders. Such 'white collar' work was socially acceptable and actively encouraged. The engineer had to know what the craftsmen were capable of producing but did not himself have to acquire the skills involved. The Romans became superb at the building of roads, bridges, tunnels, and towns and cities with their associated systems of water supply and drainage. It has been estimated that 80 000 kilometres of major roads were built throughout their Empire.

Roman engineering, and the attitude to it which prevailed at the time, was recorded by Vitruvius in his book 'De Architecture'. Vitruvius was a military engineer under Julius Caesar in the first century BC. His book gives much practical advice on the construction of buildings, finding water and testing it, properties of rain-water, methods of levelling, the waxing and waning of the moon, the sun's course through the sky and length of day, axles, pulleys, steelyards, tillers, oars, sails, yokes for oxen, pumps and military engines. In a section on the training of architects he states that 'a man who, without culture, aims at manual skill, cannot gain a prestige corresponding to his labours, while those who trust to theory and literature follow a shadow not reality; only those who have mastered both attain their purposes'. 'The architect should be a man of letters to keep a record of useful precedents; a skilful draughtsman who can represent by coloured drawings the effect desired; a mathematician who can use rule and compass, lay out works, use optics to consider the effect of light and arithmetic to add up costs; a historian to give an account of events in his decorations; a diligent student of philosophy to make him high-minded, not arrogant, fair-minded, without avarice, also understanding the principles of nature and the flow of water; not ignorant of medicine for works of water supply and drainage; learned in the law for contracts, specifications and disputes; and, finally, familiar with astronomy and astronomical calculations.' Put into modern terminology, this would be quite a reasonable account of what is required of an engineer today.

With the recording of the rules-of-thumb accumulated for designing man's constructions – and we may assume that Vitruvius was not alone in doing this – we could say that craft had by now developed into technics[1]. Although no doubt some theoretical backing was provided for a few of these rules-of-thumb, notably by Euclidean geometry, such backing was minimal. Looking at the various crafts in as much detail as the work of archaeologists permits, it does not appear that they were developed other than by a combination of invention and manipulative skill. It is very doubtful if the craftsmen, or the engineers who made use of them for major projects, knew why their techniques worked; or indeed whether they ever posed that kind of question. Progress seems much more likely to have been by chance discoveries and trial-and-error experiments, than by the sustained use of the intellect combined with experiments designed to analyse and explain the phenomena involved. Only the latter can be dignified by the term technology. Before continuing with the history of technics, let us look at what was happening on the intellectual front while all these crafts were being developed and methods of organising large projects by engineers were being established.

Natural philosophy 3000 BC to AD 1400

We know nothing of the way in which the transition from animal noises to language took place. All we have are works of imagination such as William Golding's The Inheritors. We can enter the history of man's thought only in about 3000 BC when the Middle Anaximandros carried Thales' line of thinking further, by suggesting that there was some even more primordial stuff than water, out of which the naturally occurring opposites, wet and dry, hot and cold, could emerge. Empedocles thought that more than one basic ingredient was necessary to explain nature and settled on air, fire, earth and water. Herakleitos took a different line and proposed that what was fundamental was, not a type of matter, but the fact that everything is in a state of flux and that nothing is permanent. (He could presumably be said to be the forefather of evolution and dialectical materialism.) Once the idea of a search for the primordial stuff of nature was left behind, the way was open for Pythagoras to think that numerical relations might be the reality behind the visible world. His observations of such things as the relationship between the length of a vibrating string and a musical note strengthened this view. Pythagoras and his school seem to have been the first group of thinkers to investigate the properties of number, as distinct from using numbers for practical purposes, and must have a good claim to be the founders of mathematics. Although they failed to invent a suitable notation, working as they did mainly with numbers of dots and lines, they did manage to lay the foundations for geometry which was to be formalised by Euclid a hundred years later. Perhaps the peak of the Greek contribution was reached when Leukippos and Demokritos originated the view that the reality of motion and the flux of things could be explained only if the ultimate basis of matter was atomic.

At no time in the history of these speculations did any Greek thinker suggest that experiments might be performed to substantiate their views. They observed nature as it was around them, and reflected upon what they saw. Although one can argue quite reasonably that they founded the branches of knowledge we call mathematics and astronomy, it would be stretching the imagination rather far to suggest that they laid the foundations of science – of natural philosophy yes, but of science no. At this point, in the fifth

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[1]This was a term used by Lewis Mumford in his classic work 'Technics and Civilisation' (Routledge, 1934).

century BC, Greek thought took a turn which was to delay the true birth of science for nearly two thousand years. These great thinkers began to worry about the contrast between the abstract concepts they had been developing and the observable physical world around them which seemed full of optical illusions. They began to be concerned with what was really real, with how we can be said to know anything other than our fleeting impressions, and with the rules for logical thinking. In other words, they became interested in philosophy.

That we know so much about Greek thought is due to Aristotle writing in the fourth century BC, and for this we must be grateful. It was no fault of his that the unsubstantiated views about nature in his books were regarded as the fount of all secular wisdom for centuries. We can blame him, however, for not always backing the most sensible and fruitful ideas: for example, that he did not accept the atomic view of matter propounded by Demokritos. Aristotle's writings were preserved by the Moors during the so-called Dark Ages in Europe, and when they were rediscovered for Christendom they came under the protection of the Christian Church. To question them became almost a matter of heresy. But this is leaping ahead too fast.

There was at least one hint of what might be achieved by science proper in the work of Archimedes in the third century BC, for he realised that experiments might be a useful way of acquiring knowledge. His work on the relative density of materials, and the principles of the lever, certainly involved experiment. He was also an inventor – of compound pulleys, hydraulic screws, burning mirrors – and of various engines of war which kept the Romans at bay for several years. But historians tell us that Archimedes regarded his mechanical contrivances as little more than playthings. His chief interest lay in geometry, and his determination of the ratio of the circumference of a circle to its diameter he regarded as his greatest achievement (he said it lay between $3\frac{10}{71}$ and $3\frac{1}{7}$). In other words, he remained inclined to the prevailing view that pure thought was on an all together higher plane than anything that smacked of craft. There is no real evidence that he explicitly used his theoretical knowledge to improve his mechanical inventions. One feels that the ingredients for the birth of both science and technology must have been there, even if they failed to crystallise, because that incredible polymath of the Renaissance, Leonardo da Vinci, sought for copies of the works of Archimedes more eagerly than for those of any other Greek philosopher. One wonders whether the 'long night' would have been quite so long had Aristotle, in his capacity as rapporteur, lived after Archimedes.

We have now completed our brief picture of the precursors of science and technology without arriving at anything that we would recognise as either. What we have is, on the one hand, a natural philosophy based on observation of nature as it is around us and providing the foundation for mathematics and astronomy, and on the other hand a variety of inventions, crafts and skills without any theoretical foundation or any attempt to explain why they worked.

To continue with our search for the true birth of science we must now jump many centuries. The reason is that the Romans contributed little to natural philosophy and, after the fall of the Roman Empire, Europe entered into five hundred years of barbarism and obscurantism. The Byzantine and Arab Empires were to become the repositories of learning until the Middle Ages, and of natural philosophy until the Renaissance. They did so by translating into Arabic the works of Aristotle, Euclid, Archimedes, Hero of Alexandria, Galen, and Ptolemy. Islam did not itself seem to contribute much to the advance of natural philosophy, although it did develop the system of Arabic numerals, acquired from India, and pass it on to Europe in the twelfth century AD.

The next great leap forward in man's intellectual development had to await the decline of the Scholasticism of Aquinas, the appearance of the Renaissance in Italy (assisted by refugee scholars from the Turkish invasion of Constantinople), and the Reformation in Germany. One cannot pass by the Middle Ages, however, without mentioning the flow of scholars to a centre of learning in Spain, Toledo, where teams of Christians, Jews and Moslems worked together to translate into Latin all the important extant works of the early Greek and Arabian natural philosophers. This tremendous labour of scholarship in the twelfth century provided the necessary springboard for the leap forward that was to follow during the Renaissance three centuries later. One must also take note of a Franciscan friar named Roger Bacon (1214–1292) who was a contemporary of Thomas Aquinas. Bacon was a prodigious scholar – of both Arabian and Greek natural philosophy – and he found himself unable to accept as authoritative the views of nature propounded by Aristotle or implied by the Bible. He argued that true knowledge of these matters could be obtained only by observation and experiment. As he put it, experiment can enable us to judge the follies of magicians just as logic can be used to test an argument. In taking this view Roger Bacon was far ahead of his time and his books had little immediate effect.

Science 1400 to 1700

After the thirteenth century, Europe was subjected to economic and social confusion caused by famines, the Black Death, and the Hundred Years' War. Although this unrest delayed further progress, it must have provided fertile ground for 'dissidents' striving for the separation of philosophy and theology. The movement was led by Duns Scotus and continued by William of Occam. The latter proclaimed the irrational nature of many of the doctrines of the Church and attacked the theory of Papal supremacy. Then came the great voyages of the fifteenth century to the New World which opened men's minds and became a source of great wealth. A proportion of this wealth became concentrated in the cities of Northern Italy which gave birth to the Renaissance. And so we come to Leonardo da Vinci (1452–1519) – painter, sculptor, engineer, architect, physicist, biologist, and philosopher – a polymath of staggering breadth of interest and much too good in each role to be called a dilettante. Here at last we meet a man to whom knowledge of principles whether of mathematics, optics, hydraulics, mechanics, physiology or anatomy was seen as something with which to improve his art and his crafts. Here at last we meet a man who actually performed experiments. 'Those sciences are vain and full of errors which are not born from experiment, the mother of all certainty, and which do not end with one clear experiment.' He dismissed astrology and alchemy as magical nonsense, and he had a greater respect for Archimedes than Aristotle. Something recognisable as science in the modern sense of the word was clearly being born in the Renaissance.

This brief historical sketch is bound to give the impression that intellectual progress over the centuries was the work of a few men. Of course this was not so. Roger Bacon, for example, was preceded one-and-a-half centuries earlier by Peter Abelard (1079-1142) who, although primarily a philosopher and logician, did theorise about the distinction between knowledge gained by constructing things or by trial-and-error, and knowledge gained by reasoning. Abelard stressed that both were important. Furthermore, Roger Bacon had a teacher, Robert Grosseteste (1175-1253), who emphasised in his writings the importance of basing natural philosophy on mathematics and experiment. From his work on optics, Grosseteste was able to suggest the use of lenses for magnification which foreshadowed the invention of spectacles a few decades after his death. Or, to take another example, Leonardo had the benefit of mixing and corresponding with many others of like mind who were specialists in various fields. Furthermore, Leonardo's circle was fortunate in living during a brief period when the Papacy itself was liberal and humanist. One needs both the man and the milieu for any substantial advance in knowledge. One remarkable feature of the period was the way both scholars and well-known craftsmen moved from city to city and from one wealthy patron to another, in spite of the hazards of travel. Without this kind of 'free-masonry' of scholars, and the international language of Latin, progress would certainly have been much slower.

The Renaissance, closely followed by the reduction in power of the Papacy consequent upon the Reformation, paved the way for the proliferation of the sciences in the fifteenth and sixteenth centuries. Progress was rapid because men of science began to specialise rather more than hitherto, as craftsmen had been doing since the earliest times, although they would still be regarded as polymaths by twentieth century standards. Picking out a few, prominent names at random, we have Copernicus (1473–1543), Tycho Brahe (1546–1601) and Kepler (1571–1630) writing on astronomy, Valerius Cordus (1575–1644) on botany, Belon (1517–1564) and Aldrovandi (1525–1606) on zoology, von Hohenheim (later called Paracelsus) (1490–1541) on medicine, Agricola (1490–1555) on mineralogy, van Helmont (1577–1644) on chemistry, Vesalius (1515–1564) on anatomy, Harvey (1578–1657) on physiology, and Gilbert (1540–1603) on magnetism and electricity. All these men also made contributions in fields quite other than those mentioned, and all recognised the importance of writing up their results: one wonders how many of the men of the sixteenth and seventeenth centuries must have wished that Leonardo had found time to publish his work. Publication was now possible because, as we shall see, the paper mill and printing press had been developed to a suitable state by 1500. Indeed, by then, pocket-sized editions of the works of Aristotle were coming off a press in Italy.

During the seventeenth century a vast number of aids to scientific work were invented: the systems of logarithms by Napier and Briggs, slide rule by Bissaker, adding machine by Pascal, improved telescopes by Huygens and reflecting telescope by Newton, micrometer by Gascoigne, barometer by Toricelli, vacuum pump by von Guericke, and compound microscope by Hooke. Many of the scientists of the day were certainly also excellent craftsmen and inventors. Scientific societies were formed: the Royal Society in England founded by Boyle and others was given its Charter in 1662, and in 1666 the French Academy was similarly recognised. The rapid dissemination of ideas promoted by these societies had a great deal to do with the exponential increase in scientific knowledge which was to continue unbroken to the present day.

The man who first tried to analyse what was at the back of all these developments – the 'scientific method' – was Francis Bacon (1561–1626). He surely deserves to be regarded as the first philosopher of science. Perhaps the real breakthrough was the realisation that one could get much further by concentrating on the *how* of things rather than the *why* of things. Pursuing this line of thought, and working with pendulums and rolling balls on inclined planes, Galileo (1564–1642) was able to establish many important principles of dynamics – for example, that a falling body moves a distance proportional to the square of the time, and that a force is required to change the magnitude or direction of the velocity of a body and not, in the absence of friction, to maintain its motion. Galileo's work was brought to fruition by Newton who was born the year Galileo died (1642). Newton's theory of gravitation (*Principia*, 1687) was the first great synthesis, in which he showed that Galileo's terrestrial results and Kepler's theory of planetary motion could be deduced from the same few simple laws of mechanics.

Here we see the first signs of what we mean by a scientific explanation of phenomena: a set of hypotheses from which all known phenomena of a particular kind can be deduced. This was the model to which all the sciences were to try to conform. A steady improvement in the accuracy of his means of measurement enabled the scientist to check more precisely the deductions drawn from the hypotheses. This often threw up anomalies which encouraged the search for refinements to the hypotheses, and which in turn suggested new experiments for their verification. In pursuing this type of programme, scientists began to study not just the world as it is, but artificial situations that they created in order to limit the number of variables for their experiments. They called on the skills of craftsmen to produce the apparatus they needed (for example, glass blowing, grinding, and polishing for thermometers, lenses and mirrors, and all kinds of metalwork), and it was natural for them to turn their attention from time to time to study the processes used by the craftsmen but little understood (for example, alloying of metals and the production of ceramics). We are evidently now at the point where technology might be seen to appear. It is time to retrace our steps to see what the craftsmen had been doing during this long period of transition from natural philosophy to science. They had not been idle, and rules-of-thumb for designing ships, furnaces, wind and water mills, and tools of all kinds, had certainly been improved.

Technics AD 500 to 1850

We left our earlier story at the point where we said that the Romans had been instrumental in spreading the use of the waterwheel throughout Europe. To emphasise its importance one may note that a slave working for ten hours could grind about 40 kg of corn, whereas the Roman mill constructed near Arles in Provence (having eight waterwheels in series in each of two millraces) could grind about 28 000 kg in a ten-hour day and regularly supply sufficient flour for eighty thousand people. Naturally the potential of water power was more fully appreciated in northern Europe where there was a plentiful supply of water the whole year round, than it was in Greece and Italy where expensive aqueducts were usually necessary adjuncts.

We can certainly pass quickly over the Dark Ages in Europe which followed the fall of the Roman Empire, but must note in passing what was happening in the Islamic world and in China. No very notable technical developments seem to have been made by Islam, but in 1205 al-Jazzari produced his *Book of Knowledge of Ingenious Mechanical Devices*. Most of the devices were little more than toys and extravagant gadgets, rather like the devices invented by Hero of Alexandria in the first century AD to whose work al-Jazzari would probably have had access. Al-Jazzari's book contained beautifully executed engineering drawings and was no doubt a source of inspiration to later inventors. The Chinese had made much technical progress in metal working, ceramics and block printing, but the invention of paper was perhaps their most significant contribution because of its ultimate effect on the dissemination of knowledge. The technique for making paper was certainly established in China before AD 150 and was used there for many centuries before it made its way to the Islamic world in the eighth century and to Europe in the thirteenth century. Water-clocks too had reached a high degree of sophistication in China by the eighth century. In the eleventh century a Chinese engineer built a vast clock operated by a waterwheel, using an escapement mechanism and having a 35-foot tower carrying a moving celestial sphere. China had its own 'Dark Ages' resulting from dynastic wars and plagues, but it is not easy to see why there was nothing corresponding to the Industrial Revolution in China. No doubt the cultural climate was unfavourable, and certainly the failure to develop a phonetic alphabet must have been a brake on progress.

Returning to Europe, the Middle Ages saw a tremendous growth in the number and variety of water-powered devices. They had been steadily increasing in number even during the Dark Ages, to meet the needs

of the people crowding into the new walled towns and cities. Floating mills with waterwheels mounted on barges moored to bridge piers were tried. So too were mills placed in estuaries to use tidal power, although they were not popular because of their intermittent operation over the tidal cycle. Most waterwheels operated millstones, but others worked drop hammers and bellows by making use of cams. By 1086, according to Domesday records, there were 5624 water mills in thirty-four English counties supporting 1 400 000 people. On some rivers the mills were at a concentration of two per kilometre. Such concentrations required the construction of dams upstream to provide sufficient head, and dam building became a recognised civil engineering activity. Many monasteries were in effect factories, with water power used for grinding corn, sieving flour, fulling cloth and tanning hides.

Having seen the advantage of tapping water power, man soon turned his attention to the wind. Windmills using sails mounted on a horizontal axis carried on a rotatable centre post (called post-mills) appeared in the twelfth century, and indeed Europe was exporting such devices to the Middle East during the late Crusades to replace the less efficient, vertical axis windmills that existed there. Companies were formed to own groups of mills, with the separation of ownership (through shareholding) and management that is common today. These concentrations were economic only if most people used the mills, and there was much social unrest when mill owners tried to prevent hand milling at home: certainly we have here a foretaste of what was to follow much later during the Industrial Revolution.

Stone quarrying, mining, weaving, iron-founding and paper-making were other industries that grew apace in the Middle Ages. The main environmental effect was the deforestation of Europe, both to clear the land for agriculture and to provide wood for building (ships required 2000 oaks per man-of-war) and charcoal fuel for the iron makers. One result of the wood shortage was the re-establishment of the brick and tile manufacturing industry which had lapsed after the departure of the Romans. Fortunately, coal was found in the thirteenth century before the last forests disappeared. It was not an unmixed blessing, however, because the first coal was extracted near the surface and had a high sulphur and bitumen content: so noxious were the fumes that the English Parliament had to pass an antipollution bill in 1388. The use of machinery in the textile industry resulted in the first use of assembly-line methods. We are told that the manufacture of cloth in Florence in the fourteenth century involved twenty-six operations each performed by a specialist.

All this activity must have been stimulated and supported by improvements in the productivity of agriculture which took place during the relatively better climatic conditions that prevailed in Europe between AD 850 and 1200. Part of this improvement in productivity was due to the vastly more widespread use of the horse, made possible by improvements in the methods of harnessing the animal and the invention of the nailed horse-shoe: a pair of horses could pull about 5000 kg in mediaeval times but only 500 kg in Roman times (the Theodosian Code of AD 438 made this a legal limit). Other sources of improvement were the development of the heavy-wheeled plough, and the use of three-field crop rotation. Crop yields more than doubled from AD 1000 to 1200.

The most highly paid of the mediaeval craftsmen were the architect-engineers who designed and supervised the building of cathedrals, castles, bridges and military equipment. Villard de Honnecourt, working in the first half of the thirteenth century, was a prominent architect-engineer whose sketchbook is extant. He writes 'you will also find strong help in drawing figures according to the lessons taught by the art of geometry': so here we have a sign of theory and practice coming together. The book includes rules-of-thumb for the solution of many building problems, and sketches of many mechanical devices from a mechanical water-powered saw to a perpetual motion machine. In mediaeval times the search for a perpetual motion machine which would deliver power was the equivalent of the ancient alchemists' search for the philosophers' stone which would turn lead into gold. Villard's sketchbook is similar in range of interest to Leonardo da Vinci's, although they were separated by two-and-a-half centuries. Perhaps the most advanced mechanical devices invented in the thirteenth century were the weight-driven clocks. The complex astronomical clock must be one of the first products of co-operation between natural philosophers (in this case astronomers) and technical men skilled in making mechanical devices. The one built by Giovanni di Dondi in the mid-fourteenth century was the most renowned. It used innovations such as oval wheels with internally cut teeth, and skew gears. His description of the clock runs to 130 000 words and the drawings are so detailed that an exact replica has been made.

Once again we have arrived at the fourteenth century where, as we have noted, famine (1315-17) and pestilence (1347-50) brought the mini-industrial revolution in Europe to an end. Climatic change for the worse was no doubt the root cause of the famine. Populations were decimated (more than halved in many areas); there were financial crises with devaluations and many bankruptcies; and in England the social unrest culminated in the Peasant's Revolt of 1381. There was to be no surplus of resources with which to support

invention and scholarship for another century. This is not quite true, because cannon and hand-guns were introduced in the fourteenth century. Unfortunately engineering was often fostered by power-hungry leaders who from earliest times had realised that battles were won more by technical superiority than anything else. The manufacture of weaponry was one craft whose development was not restricted by the chaos of the fourteenth century.

Perhaps the technical advance which had the most impact on the resurgence of scholarship in the Renaissance was the multiple invention of movable metal type, oil-based ink, and the printing press, by Gutenberg in the mid-fifteenth century. Movable type had certainly been used for some centuries in the Far East, but it was Gutenberg who perfected the process and started the printing industry in Europe. When combined with the output of the paper mills, man at last had an economical method of mass-producing books. The subsequent progress of science must have been as much due to easy access to each other's work as to the availability of new instruments and apparatus. It is not surprising that the first book to be printed was the Bible (1456), and that this should be closely followed by a book on military engineering *De re militari* by Valturio (1472). Leonardo da Vinci certainly possessed a copy of Valturio's book. It is from this time onwards that a master craftsman could with advantage be literate: for example, any mining engineer would have liked to have been able to read Agricola's handbook *De re Metallica* published in 1556, after his death.

The next great step forward had to await a solution to the problem of extracting water from mines – particularly coal mines – to permit the working of deeper deposits. Pumps operated by waterwheels were inadequate. The Industrial Revolution started in England, and if anyone can lay claim to have been its founder it was Thomas Newcomen who developed an idea of Thomas Savery for using condensing steam to operate a pump. The Newcomen beam engine started life in 1712. After steam had raised a piston, cold water was injected to condense the steam and the resulting partial vacuum allowed atmospheric pressure on top of the piston to provide the power stroke. The suction pump situated down the mine shaft was operated by a long rod attached to the rocking beam. This engine was not superseded until James Watt saw the advantage of using steam for the power stroke and carrying out the condensing process in a separate component. The advantage was that the massive cylinder and piston no longer had to be repeatedly heated and cooled. Boulton and Watt engines (Boulton being the business partner) were to dominate the scene from about 1765 to 1800, and were used not only for pumping but also as winding engines for hoisting men and coal up the mine shaft. After 1800, when the Boulton and Watt patent expired, there was a succession of improvements: notably the replacement of the beam by a connecting rod, crank and flywheel, and the use of higher steam pressures.

These developments dovetailed perfectly with the expansion of the iron industry, which followed the substitution of coke for charcoal as the reducing agent by Abraham Darby in 1707. Appropriately enough, remembering the starting point of our history of craft, Darby's first product was a pot – a cast iron cooking pot. Soon, however, his firm was casting iron rails for colliery trucks, and components for mills, Boulton and Watt engines and cast iron bridges.

Another great industry the textile industry – received a boost from the invention of the flying shuttle by John Kay in 1732. Rapid expansion occurred after the water-powered mechanisation of spinning (Hargreaves, 1764), of carding (Arkwright, 1767), and of the weaving looms themselves (Cartwright, 1784). Finally, steam power replaced water power, allowing a greater concentration of machinery in factories (still to be called mills). The introduction of cotton enabled the new methods to become established in the face of opposition from workers in the woollen industry who quite naturally did not see the move from cottage to factory as an unmixed blessing.

Simultaneously there was a tremendous growth in the pottery industry once John Astbury (1720) found that the addition of ground flint to the clay would make a white body. First waterwheels, then steam engines, were used to operate the millstones which ground the flint. When this innovation was combined with the discovery of kaolin ('china clay') deposits in Cornwall in the 1760s, and Josiah Wedgewood had introduced his machines for mixing the ingredients in consistent proportions, the pottery industry came of age. It had begun in Staffordshire where there were suitable deposits of ordinary clay and a plentiful supply of coal for the kilns: that it was able to remain and expand there was due to simultaneous improvements in methods of transport – to convey the kaolin and flint to the potteries and the products to the ports.

The first attempt to provide industry with the necessary transport facilities was the spate of canal building by Brindley and Telford during the years 1760 to 1820. Towards the end of this period, work on mobile steam engines for collieries had begun, culminating in the opening of the Stockton and Darlington railway in 1825 and Stephenson's *Rocket* in 1829. After that the clear advantage of speed possessed by the steam

locomotive meant that the canals were to steadily lose ground to the railways.

The last fifty years of the period that we are considering, that is 1800-1850, were enormously fruitful. We have talked so far only of the major industries, but the number of other innovations in this period, which were to be of great significance later, was staggering. The manufacture of the equipment for the major industries could not have been possible without the range of increasingly accurate machine tools introduced by Bramah and Maudsley from 1798 to 1830: work which was carried on by Whitworth, Maudsley's famous pupil. Such was Whitworth's passion for accurate measurement that he can rightly be called the father of metrology. As a result of these machine tools, interchangeability of parts became possible, so ushering in the era of mass production. Many American inventions were directed to this end, such as Fitch's capstan lathe and Root's universal milling machine.

A host of earlier ideas now became economic propositions: we have, for example, Singer's sewing machine (1851), ideas for which had been patented since 1790. There were such diverse inventions as Davy's safety lamp for miners, Gillot's machine-made steel pen, Bramah's flushing toilet with the all-important U-bend, Colt's revolver, and McCormick's reaping machine. Lebon and Murdoch introduced coal-gas lighting and a London street was lit in this way in 1807. Various forms of telegraphy were introduced, notably the Cooke and Wheatstone system in use on U.K. railways by 1845, and the American Morse system used first for business communications in the same year. The foundation of photography was laid by Talbot and Daguerre. Great advances were made in printing machinery by Stanhope and Koenig, the latter being the first to use a cylinder instead of a platen. Babbage produced a prototype calculating machine, and Oested a laboratory-scale electric motor and generator. Brunel, with his *Great Britain* (1843), ushered in the era of the iron ship powered by steam engines driving propellers.

Up to about 1800, almost the whole of this great Industrial Revolution was the work of engineers and craftsmen who happened to possess exceptional creativity and organisational ability. Virtually all the innovators had acquired their knowledge and skill through an apprenticeship and practical experience, not through formal education. There was as yet little theoretical backing for these great technical achievements so that, in the strict sense of the word, technology had still not appeared. If technology means anything, it must mean the study and reasoned account of technical processes. During the period 1800-1850, however, there is a discernible change in the way that innovations developed and we may be forced to recognise that technics had changed their character: something had been added to craft so that what was happening was not mere isolated invention coupled with manipulative skill. Before we can examine this suggestion in more detail, to see if what can only be called technology has at last arrived on the scene, we must carry our history of science up to 1850 also.

Science 1700 to 1850

We have suggested that science proper, as opposed to natural philosophy, began with the Renaissance (-1400); and we carried our account as far as Newton's achievement of 1687. What was happening to the various sciences during the Industrial Revolution between 1700 and 1850? It was in fact a period in which mysterious weightless fluids were being exorcised – phlogiston, caloric, electric fluids – as scientists struggled to find as sure a basis for the development of their subjects as Newton had supplied for mechanics.

Great strides were being made in mathematics during this period by Lagrange (1738–1813), Laplace (1747–1827) and Fourier (1768–1830), to name but three of many who made advances that were to be of considerable use to physics. But, as a crude generalisation (and this whole short account can be nothing else), developments in mathematics precede their application by at least fifty years, and they are in any case not strictly relevant to this discussion.

We can also pass quickly over developments in the sciences of botany, zoology and physiology. Progress in the grinding of lenses had brought the compound microscope, invented by Janssen in about 1590, to a useful pitch of perfection by 1650. This enabled the structure and function of organs to be studied as never before: Linnaeus (1707–1778) was able to produce his *Species Plantarum,* Buffon (1707–1788) his *Natural History of Animals,* and Heller (1708–1777) his *Elementa Physiologiae.* It was in this period that the idea of placing man in the order of primates was seriously mooted, so paving the way for the Darwinian revolution which followed publication of *The Origin of Species* in 1859. This was the third major change in the way man saw himself in relation to the universe: the first was just after the Renaissance when Copernicus (1473–1543) placed the earth in its correct perspective as a planet of the sun, and the second when Newton showed that terrestrial and astronomical phenomena were governed by the same laws. Many years and much

argument were needed after each of these intellectual revolutions before the ideas could be assimilated by religion and philosophy, and still more before they could become part of the conventional wisdom of the common man.

What was happening to chemistry during this burgeoning of science? Why do we not find this science having an impact on the Industrial Revolution? After all, so much depended on combustion – in the furnaces of the iron founders, the boilers of the engine makers, and the kilns of the potters. The answer is that chemistry was at too early a stage. Lavoisier (1745–1794) set chemistry on the right path when his experiments destroyed the phlogiston theory of combustion, and also enabled the true nature of water to be established. He paved the way for the work of Avogadro (1776–1856) who discovered the part played by molecules in chemical reactions, and the work of Cannizzaro who in 1858 was able to integrate Avogadro's ideas with Dalton's atomic theory of matter (1808). All this provided a proper foundation for the table of atomic weights. Once the idea of a chemical element was firmly established, each having its own properties and atomic weight, the search began for the connection between them. When about ninety elements had been isolated, it was possible for Mendeleev (1834–1907) to produce his Periodic Table and predict that other elements would be discovered to fill the gaps. It is quite clear that when chemists were just beginning to be able to write down chemical equations, they could hardly have much to contribute to the analysis and improvement of the complex processes being used by the manufacturing industries. Neither, at this stage, was chemistry of much help to agriculture. Liebig (1803–1873), who with Dumas (1800–1884) was co-founder of organic chemistry, correctly recognised the vital part played by carbon and nitrogen in plant growth but specifically denied the importance of humus in the soil. His recommendations led to incorrect treatment of the soil and eventually to the dust bowls that were to follow.

Let us now return to physics, and see first what had been happening to the ideas scientists had been having about the nature of heat. Joseph Black (1728–1799) began the task of clearing up the confusion between heat and temperature, but unfortunately introduced the idea of a weightless fluid, caloric, to explain the phenomena of conduction and changes of phase between solid and liquid or liquid and vapour. The name is still with us in the term 'calorimetry'. The caloric theory persisted until Joule (1818–1889) showed conclusively that there was an equivalence between heat and work and that heat was a mode of motion. A confusion between the concepts of 'force' and 'energy' still remained, however, until resolved by William Thomson (Lord Kelvin) (1824–1907) and Clausius (1822–1888). It was a young French engineer, Sadi Carnot (1795–1832), who was to put these great minds on the right road. Carnot bent his mind to the problem of explaining what went on in a steam engine. He saw the necessity for thinking about what happens when a fluid is taken through a complete cycle of ideal frictionless processes. He argued that both a hot source and cold sink of heat were essential if work was to be produced, and that his ideal cycle would provide a measure of the maximum work that could be obtained with given temperatures in the boiler and condenser. Carnot can rightly be said to be the founder of thermodynamics. His argument was faulty because he thought in terms of the caloric theory of heat, but his conclusions were sound and laid the foundation for the statements of the Second Law of Thermodynamics proposed by Kelvin and Clausius. All this came well after the development of the steam engines which made the Industrial Revolution possible.

One must make the point here, to which we will return later, that the inability of science to help the industrialists was no great loss. At this stage no one was greatly concerned with the 'efficiency' of the processes in the furnaces, boilers, engines, condensers and kilns: that they worked at all was quite enough. Only when competition or scarcity of resources arouses concern with 'efficiency' does one have to analyse what is going on in the plant.

One branch of physics which blossomed in this period, and which had no corresponding preceding development in industry, was electricity. All the earlier work had been with static electricity produced by friction, but in 1800 Volta 'invented' a pile of zinc, copper and brine-soaked paper discs which produced a steady potential across the terminals. Invented is in inverted commas because it was by no means a chance discovery: it was the result of a series of careful experiments suggested by the fact that a frog's leg convulsed when touched with a metal scalpel, as reported by the physiologist Galvani (1737–1798). Nicholson and Carlisle immediately found that suitable electrodes connected to the pile would decompose water, and the science of electrochemistry was born. Faraday (1791–1867) discovered the two fundamental laws of this science: that the mass liberated is proportional to the quantity of electricity (that is, $current \times time$), and that it is proportional to the chemical equivalent weight (not atomic weight) of the substance. The first law enabled a unit of electric current, the ampere, to be defined. Other important phenomena were noted during this period, such as the thermoelectric effect, (Seebeck, 1822), the ability of a current in a neighbouring wire to deflect a compass needle (Oersted, 1820), and that one current-carrying coil exerted a force in another

(Ampère, 1775–1836). The laws discovered by Ampère and Ohm (1781–1854) laid a firm foundation for a theory of electricity.

One must note here that Volta was able to perform his experiments only because of improvements in the sensitivity of electroscopes. And it was the torsion balance invented in 1784 by Coulomb (another French engineer) that gave Ampère his idea for the galvanometer and enabled him to perform quantitative experiments which could lead to the formulation of general laws. Furthermore, the torsion balance was made possible only by metallurgical techniques that had been devised for drawing out fine wires. There must be many reasons for the great expansion of science in this period, but one was certainly the ability of craftsmen to make the wide variety of glassware and instruments required, which at last enabled reasonably accurate experiments to be performed.
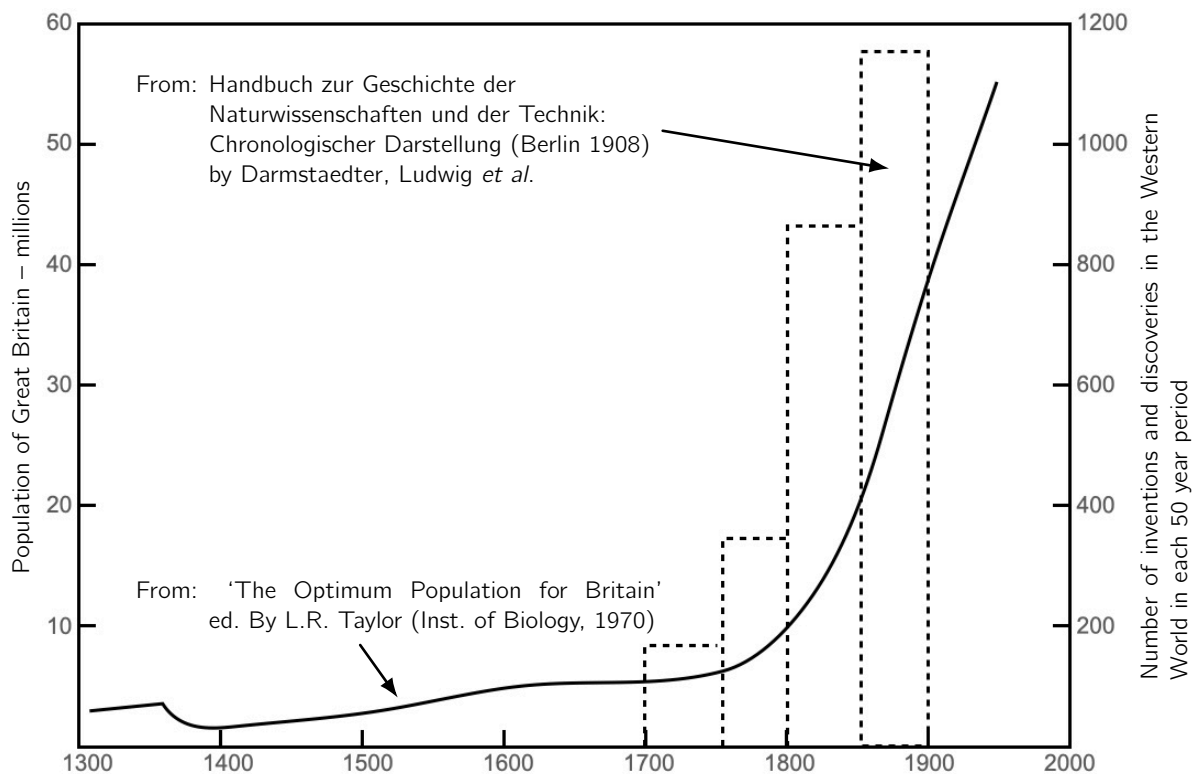

Figure 2.1: Increase in population and number of inventions

Another reason may have been the rapid increase in the population which started in the 1700s and continued unabated until the early 1900s. Figure 2.1 shows the change in population of Britain from 1300 to the present day, but much the same trend was followed in Europe as a whole. Also shown are the number of technical discoveries and inventions during each half-century between 1700 and 1900 (although not limited to Britain). The correspondence may be mere coincidence: on the other hand, it may be that a more or less fixed proportion of any population is born with the capacity for technical and scientific innovation. Bearing in mind that many innovators were responsible for more than one invention or discovery, and that the population of Europe was several times that of Britain, one might deduce a figure of 1 in 100 000 which is not unreasonable. Of course, this simplistic view of the relationship between population and innovation cannot be pressed too far. Innovation is self-perpetuating and recent additions, such as computer technology, together with the expansion of information and education services, will lead to a continuing upward movement of the innovation curve even though population growth in the developed world is levelling off.

The rise in population from 1750 must have been a function of the wealth produced by the Industrial Revolution. That the rate of increase was maintained was due to improvements in health following the purification of water supplies and better hygiene generally, coupled with the introduction of vaccination and inoculation. The identification of disease with microbes by Pasteur (1833-1895) was the first step on this road. The net result was that the annual death-rate in major cities was drastically reduced: in London the

figure fell from about eight per cent in 1750 to 1.2 per cent in 1928.

We have now brought our historical surveys of craft/technics/ technology and natural philosophy/science up to the same date, 1850, and for our purpose we need not carry the story any further. After 1850 we have a steady increase in the number of quite new industries, associated with electrical power, petroleum fuel, internal combustion engines, turbines, automobiles, aircraft, chemicals, plastics including man-made fibres, electronics (wireless, television, and telecommunications generally), nuclear power, computers, micro-electronics, bio-engineering, and finally space exploration. Most of these are inextricably bound up with the sciences on which they are based – principally physics and chemistry – and all have led to the development of separate subjects of study which are the province of technologists and not scientists. Earlier we suggested that the period 1800-1850 is the one most likely to be helpful in deciding when the transition from technics to technology took place. Perhaps we can learn something useful from the way in which the education of engineers had been developing up to this period.

Development of engineering education

We have said that technology must be more than invention combined with manipulative skill, and that it must involve the study and reasoned account of man-made technical processes. It must surely also involve both theory and experiment designed to explain and improve these processes. It follows that we should look at how educational institutions had been developing. In 1600, the fifty or so universities that existed in the Western World were still devoted to classical learning and mathematics, and they provided training mainly for the Church and the legal profession. Even medicine was only recognised as an academic subject after 1656 when a chair was established in Leyden University. That something more was required was expressed in various utopias conceived about this time: Thomas More in his *Utopia* advocated trade schools to upgrade the technical skills of the poor, and Francis Bacon in his *New Atlantis* went further and postulated a 'House of Solomon' which was a technical institute for teaching and research in crafts, engineering, agriculture and science. Over a long period, various writers from Descartes (1596-1650) to Voltaire (1694-1779) were to stress the need for something of this kind. There were, however, no national systems of education upon which to build, because literacy was not yet seen as being necessary for craft training. The Guilds had traditionally controlled craft training via apprenticeships, that is, learning by doing.

The scientific societies of the period were also aware of the need and saw themselves as doing more than merely fostering science. Hooke, one of the founder members of the Royal Society, said that its purpose was 'to improve the knowledge of natural things and all useful Arts, Manufactures, Mechanick practices, Engines and Inventions by Experiments'. Boyle, another founder member, expressed the belief that much useful chemical and metallurgical knowledge was to be gained by studying the practices of craftsmen. These scientific societies recorded the results and achievements of the practical men of the time, but how was it to be disseminated?

We have observed that originally the term engineer referred to those who specialised in the construction of military equipment and fortifications. By the seventeenth century the skills required of the military engineer had widened enormously, and he certainly had to know some mathematics and have a working knowledge of hydraulics, surveying, architecture and machine elements. But all this information was still being passed on through the master/pupil relationship, even though a number of treatises had been written on these various topics. It was the French who first realised the need for more formal education of their engineers, and from about 1690 onwards, the government set up a number of 'artillery schools', which eventually led to the establishment of the École du genie in 1749. The professors in these schools, mostly mathematicians, wrote textbooks on their various interests: for example, Belidor wrote a six-volume work entitled *La Science des engénieurs* (1729) dealing with structures and mechanics, and *Architecture Hydraulique* (1737) dealing with canals and water-works, bridges and harbours. In 1772 Bezout published a six-volume work called *Cours des mathématiques* with applications to gunnery, naval construction and navigation; and in 1795 Monge produced a manual of engineering drawing called *Geometrie descriptive*. These efforts to systematise engineering knowledge led to the establishment of the prestigious École Polytechnique in 1794 from which Sadi Carnot graduated.

There was soon to be a national education system, and entrance to the École Polytechnique was by a stiff examination. Finally, during the nineteenth century, the École Polytechnique came to be treated as a feeder for more specialised Écoles d'application where the practical aspects of the curriculum were taught.

Germany followed in a similar vein – with institutions initiated and controlled by the government – but

Britain did not. A military college was established in Woolwich in 1741, but by then the industrial revolution was directing people's attention more to the needs of industry than to those of the military. Furthermore, efforts to meet the need were left to the initiative of industrialists, in line with the political freedom enjoyed by Britain under Parliament after Charles I had been disposed of. At first the need was met by itinerant lecturers who toured the industrial towns with their courses. Some of these lecturers, and practising engineers also, produced textbooks which helped to provide the basis for the more formal educational provision which was to follow: for example, Switzer's *Hydrostaticks and Hydraulicks* in 1729, Emerson's *Fluxions and Mechanics* in 1743, Valency's *Treatise on Inland Navigation* in 1763, and Smeaton's *Experimental Enquiry into the Natural Powers of Wind and Water to turn Mills* in 1794.

It should not be supposed that even the master craftsmen of the day took much notice of these books. The output of people like Euler and Bernoulli, which was to have a great influence later on engineering science, was probably read only by other mathematicians. Although the leading engineers of the time certainly made use of the more straightforward analytical techniques that were available, they quite rightly did not place much reliance upon theoretical results. Telford, for example, although widely read, was scathing about mathematicians who tried to advance theories about bridge building. One of the criticisms was that the mathematicians took little account of the variable forces of nature with which the practical men had to contend. The final result of these early efforts in Britain to systematise and disseminate the collective experience of practical men and the work of applied mathematicians was the formation of the Institution of Civil Engineers in 1820 with Telford as its first president.

Worried by the effect that the formal education of large numbers of continental engineering students might have on Britain's industrial supremacy, some far-sighted men started *The Mechanics Magazine* for intelligent mechanics in 1824, and in the same year the first Mechanic's Institute was opened in Glasgow. That Scotland should have led the way was not surprising, because the Scottish education system was far in advance of England's. By 1850, however, there were 610 Mechanics Institutes throughout Britain, and apprentices were being given a background of scientific knowledge to buttress their practical training. Emphasis was laid on those aspects of science which might have industrial applications.

What was probably the first engineering course in Cambridge University was given by William Farish, Jacksonian Professor of Natural Experimental Philosophy from 1813 to 1836. He surveyed the whole industrial scene in his lectures and tried to convey the principles behind the various processes. He dealt with mining and smelting of ores; metal manufacture; processes by which the common chemicals were obtained; textile manufacturing methods including the processes of bleaching, dyeing and printing, waterwheels, windmills, and steam engines; canals, bridges and harbours; and naval architecture. The idea was to 'excite the attention of persons already acquainted with the principles of Mathematics, Philosophy and Chemistry, to Real Practice'. Farish's successor gave a course on 'Statics, Dynamics and Mechanism with practical application to manufacturing processes, to Engineering and Architecture'. His efforts led to the establishment of the first chair in 'Mechanism and Engineering' at Cambridge in 1875. Meanwhile the newer universities – notably the London colleges – had for some time had chairs in mechanical and civil engineering and were offering degrees in these subjects. Rankine, perhaps the most celebrated engineering professor of the period, had studied a wide range of subjects at Edinburgh University, served an apprenticeship, worked as an engineer on many civil engineering projects, and published his famous papers on thermodynamics, before he became a professor at Glasgow University in 1855. Thereafter he proceeded to astonish his colleagues with a constant flow of original fundamental work.

Although many of the early efforts to educate the 'mechanic' must have disseminated a little basic science and mathematics, the major part of the courses will have merely described the industrial techniques of the time without much delineation of principles. By 1850, however, there had been developed a body of knowledge distinct from science, which was the province of the technologist and which had to be mastered by anyone hoping to become an engineer. Nearly a century had to pass before this was to be disseminated widely by full-time higher education in Britain, and meanwhile most engineers continued to be trained by apprenticeship, evening classes and private study. Be that as it may, the body of knowledge was there, produced by a blend of (a) the work of applied mathematicians, (b) the experiments of practical engineers and of some scientists who took an interest in technical processes, and (c) rules-of-thumb developed over the centuries. While it is not possible to ascribe the birth of technology to a particular set of events, it is possible to argue that technology came of age during the period 1800 to 1850. From this period onwards science and technology developed side by side, each supporting and stimulating the other.

Some characteristics of science and technology

We are now in a position to outline some of the obvious characteristics of science and technology, before trying to deal with the more detailed philosophical questions listed in the Introduction. We have seen that science grew out of natural philosophy, the latter being the name given to speculation about the structure and behaviour of the natural world based on direct observation of phenomena. As natural philosophy progressed it involved the classification of phenomena and some degree of concentration by individuals upon each category. It is not surprising that astronomy was the first study to reach a high state of development because it deals with natural phenomena which can only be observed there is no question of them being subjected to experiment under controlled conditions. Astronomical observations became progressively more accurate as the technique of making telescopes improved, and eventually the planetary motions were described in a detailed quantitative and consistent way. No physical explanation of the motions could be given, and indeed prior to the birth of science most people were satisfied with explanations of the form 'ordained by god' or 'it is in the nature of the thing'.

As far as terrestrial phenomena were concerned, in mechanics and optics for example, it was eventually realised that only repeatable experiments could lead to agreement between natural philosophers, and to a body of certain knowledge which could be added to step by step. Therein lay the birth of science. Certain though it may be (and just how certain we shall examine later), the knowledge was of a strictly limited kind because it was concerned mainly with how things behaved rather than why. For this reason few scientific discoveries were in direct conflict with the Church's teaching. In those cases where the Church did react, it did so because it feared the eventual impact of the discovery on the minds of ordinary people who could not be expected to appreciate the limited nature of the scientists' work.

Science came of age with Newton's *Principia* which showed the connection between astronomical and terrestrial phenomena. Both, it now appeared, could be described in terms of the same few principles or 'laws' of mechanics. It is in this sense only that science can be said to 'explain' phenomena. A concept like gravity, even if highly abstract and not expressible in terms of something obvious to the senses, is entirely satisfactory if it leads to a theory from which the behaviour of widely different systems can be deduced. The laws of science give us a satisfying feeling that we are understanding nature, because they are capable of predicting what will happen under specified circumstances: they bestow on us both a psychological and a practical benefit. They make use of the notion of internal cause and effect, and we no longer feel at the mercy of diverse gods. This is a very real advantage because we are thereby encouraged to try to take avoiding action, and with increasing knowledge we are often successful in so doing, particularly in the biological and medical spheres.

This brings us conveniently to technology, the mainspring of which is the belief that our environment can be manipulated to our advantage. We have seen that technology grew out of craft and that craft pre-dated natural philosophy by many millennia. This is not surprising because natural philosophy required an advanced written language with a full vocabulary to supplement man's innate curiosity about his environment, whereas craft merely required an inventive streak coupled with manual dexterity. Rules-of-thumb were soon accumulated for designing everything man constructed – from waterwheels to engines of war, from canals to cathedrals.

This is the age of technics. During the Industrial Revolution a vast range of new technical processes and machines were invented, but that they worked was virtually all that was asked of them. As this revolution spread throughout Europe and America, competition forced the engineers to consider the efficiency of their processes and appliances. They looked increasingly for help from applied mathematicians and interested scientists, and began to perform experiments to determine the properties of the materials that they were using, and the strength of the structures that they were creating. Bodies of useful theory were formulated concerned with materials, machines, hydraulics, and structural design. These were soon to be followed by many more as a variety of technologies were spawned by the developing sciences of physics and chemistry. These bodies of technological knowledge do differ from the sciences, and it is the precise nature of the difference that we will examine in detail in the next chapter.

The main causes of the difference we can deal with straight away, and they are threefold. Firstly, there is the different purpose in the minds of the scientist and technologist. From our historical account it should be clear that the scientist's purpose is to try to understand the world around himself. Originally this was the natural world, virtually unchanged by man's endeavours: nowadays it is a world modified very considerably by man's technological achievements. A solid-state physicist, for example, may well find himself studying the behaviour of new materials created by the technologist, in his search for answers to fundamental questions

about the nature of atomic forces. The technologist's main purpose, however, is to meet some human need (other than satisfying man's curiosity) perceived either by himself or by someone else. He may also be studying the behaviour of the materials occupying the attention of the solid-state physicist, but he will be doing quite different experiments because he is likely to be interested only in the macroscopic properties of the material. His object is to enable the material to be used more effectively in the construction of some artefact or structure. This major difference in attitude between the scientist and technologist might properly be referred to as the *teleological* distinction because it relates to purposes or aims.

The second cause of the difference in the nature of science and technology lies in the basic presuppositions behind these two human endeavours. Science, we have observed, presupposes a certain regularity in nature. Science became possible only when the notion of natural cause and effect replaced the idea that the flux of things was due to the whims of the gods. While this is also an important presupposition of technology, we have seen that there is a more fundamental one – at least it is prior in the historical sense – and that is that nature is capable of manipulation and modification, the better to serve human needs. This is why technological progress is essentially the endless quest for more and more diversified objects and better means for producing them – better in the sense of more economic (that is, less energy, materials, labour or time), or better in the sense that the product is more effective for its purpose. Scientific progress is quite different: it is an endless quest for better theories and concepts to explain phenomena. Here better may mean simpler, more universal, or having greater explanatory and predictive power.

Thirdly, economic and social considerations play a much more important role in technology than in science. This is because in principle the products of technology are available to all, and all are directly affected by technology in one way or another. For this reason too, technology involves the use of a variety of codes of standards based on society's evaluation of what it is reasonable to expect in matters of safety, reliability, durability and aesthetics. Science is a more private activity, certainly in the sense that its product – knowledge – does not have to be available to all, that is, be understandable by all. This is not to say that science has no social implications, or that no codes of standards exist. There are codes of practice associated with animal experiments and genetic experiments, for example, and no doubt others will arise in the future. Such considerations do not, however, play a central role in science.

Finally, we might end by pointing out one similarity between science and technology which clearly distinguishes them from the arts and social sciences. Both the scientist and technologist study events which are substantially unaffected by the process of study itself. Three important consequences follow. Firstly, the results can be expressed in quite impersonal terms; secondly, the results are repeatable; and thirdly, they should be acceptable to any rational person. The arts, as we shall argue in the first section of chapter 4, are concerned essentially with the expression of an individual's personal emotional experience of aspects of the world, whether through literature, music or the graphic arts. The artist will, of course, hope that he is dealing with sufficiently basic human experiences for his work to strike a chord in the minds of other people. The extent to which he is successful in doing this is a measure of the depth and quality of his art. But he knows that no two human beings' emotional experiences are identical, and therein lies the challenge of his endeavour. The social sciences – economics, psychology, sociology and so on – try to adopt the objective stance of science and technology, but differ from them in that the objects of study are markedly affected by the process of study. As a consequence the results are seldom repeatable, and so far the theories have lacked sure foundations which can be accepted for building on by successive generations.

This is, of course, not the fault of the social scientists, but follows from (a) the intractable nature of their continuously changing subject matter, (b) the difficulty of defining unambiguously the concepts used in their theorising (for example, gross national product, intelligence quotient, extrovert/introvert, social classes), and (c) the impossibility of quantifying these concepts in such a way that they can be manipulated mathematically to yield results which can be confirmed or falsified.

Chapter 3

Scientific and Technological Explanation

What is meant by explanation?; scientific explanation; historical explanation; technological explanation; engineering, technology and engineering science.

At the end of chapter 2 we noted an important difference between the *aims* of science and technology, which we called the teleological distinction. One consequence is as follows. In its effort to explain phenomena, a scientific investigation can wander at will as unforeseen results suggest new paths to follow. Moreover, such investigations never end because they always throw up further questions. The essence of technological investigations is that they are directed towards serving the process of designing and manufacturing or constructing particular things whose purpose has been clearly defined. We may wish to design a bridge that uses less material, build a dam that is safer; improve the efficiency of a power station, travel faster on the railways, and so on. A technological investigation is in this sense more prescribed than a scientific investigation. It is also more limited, in that it may end when it has led to an adequate solution of a technical problem. The investigation may be restarted if there is renewed interest in the product, either because of changing social or economic circumstances or because favourable developments in a neighbouring technology make a new advance possible. On the other hand it may come to a complete stop because the product has been entirely superseded by something else that will meet humanity's changing needs rather better.

It could be that this difference will be found to lead to a corresponding difference between scientific and technological explanation of phenomena. Because of its limited purpose, a technological explanation will certainly involve a level of approximation that is unacceptable in science. But is there a more fundamental distinction? Before examining this question in detail, let us look briefly at what is usually meant by explanation in general.

What is meant by explanation?

We hope for two distinct things from an explanation: a psychological benefit and a practical benefit. Firstly, we expect an assuaging of our curiosity a replacement of an uncomfortable mental sensation of not knowing with the intellectual satisfaction of knowing. This sense of mental comfort can be provided in different ways, is usually only temporary, and never complete. Secondly, we expect some practical benefit in the form of an increased ability to mould our environment in accordance with our wishes. For this to be possible the explanation must enable us to make predictions about future events. The ability to control the environment is essential for human beings because, unlike most other organisms, we are not equipped with sufficient built-in, inherited, forms of behaviour to secure our survival. This is true whether we are thinking of physical or social environments.

We can distinguish two quite distinct types of explanation, only one of which can adequately serve both these purposes. Let us consider the following situation. Father, being one of the 'top people', is reading *The Times* in a room with his three sons. The conversation goes something like this:

(a) The youngest son starts the ball rolling: 'Why is the cat scratching at the door Daddy?' Answer: 'Because it wants to get in.' This is an explanation in terms of a goal or purpose, that is, a teleological

explanation. It will be perfectly satisfying to the youngest son, but its value for prediction is nil. On another occasion the cat might be merely wishing to sharpen its claws.

(b) Now the middle son chimes in: 'But why does the cat want to get in?' The answer might be: 'Because it wants to get at the saucer of milk.' Again, this is a purely teleological explanation, and because it is only one of many possible goals its predictive value is nil. But Father might reply: 'Because there is a saucer of milk here and all cats like milk.' Although still mainly teleological, this explanation does perhaps have the beginnings of another kind of explanation, a *causal* explanation, because it involves the empirical generalisation that 'all cats like milk'. To this extent it has some predictive value. Because 'all cats like milk', the existence of the saucer of milk in the room makes it likely that the teleological element in the explanation is correct.

(c) The middle son is satisfied, but not so the oldest son. Lifting his head from his homework he says: 'Say Pop, what is it about a cat's metabolism that makes it like milk?' The actual and immediate answer would have to be a causal explanation in terms of biochemical laws. And this would certainly satisfy the oldest son because he is adequately prepared by A-level G.C.E. to be blinded by science.

(d) The last act in our saga is a silent Father wondering why the biochemical laws are what they are. The answer could be either a teleological explanation in terms of God's purpose or nature's purpose, or a causal one if some more general scientific laws could be quoted from which the biochemical laws are deducible. The teleological explanation is final, if unsatisfying, but the causal type can never be final. In spite of this, it is the causal explanation which has the greater predictive power. Although it will normally be hedged about with restrictions on the circumstances in which it is applicable, provided that these are met we can usually expect not only qualitative but quantitative predictions.

The basic reason why a teleological explanation has little predictive power is that it is explaining a present event by reference to a future event in the sense of a purpose to be achieved. It is also psychologically much less satisfying than a causal explanation whereby a present event is explained with reference to either a logically prior, or temporally prior, event. A critic from the 'other culture' might say that because causal laws can never be final explanations they are only answers to 'how' questions and not 'why' questions. In other words that they are merely descriptions of what happens. They are, however, more than this, because if true they cover all instances that have not been observed as well as those that have. They evidently have a predictive power that mere descriptions or enumerations of events do not have.

Scientific explanation

Teleological explanations are often used in the early days of a science – particularly in the development of the biological and psychological sciences. 'Why is the heart beating? – To circulate the blood around the body.' Here an intention is ascribed to the biological organ. One should not despise such explanations – no one would deny the great step forward in our understanding of the body due to Harvey's theory of the circulation of the blood. But it is a first-stage explanation only, and nowadays one feels more comfortable if such explanations can be given in terms of chemistry or physics: in our example it would be in terms of the biochemistry of blood.

A word of warning is in order here. Just because one sort of explanation is 'reduced' to another as a science develops, it does not necessarily mean that the early type loses all its value. Classical thermodynamics is still useful even though, with suitable assumptions, it can be reduced to statistical mechanics. Both theories make use of abstract concepts, and it makes little sense to indulge in inconclusive argument about which is the truer representation of reality. What is important is that the theories, each in their own way, should enable useful predictions to be made. Or, to take a simple analogy, suppose the time arrives when the detailed physical and chemical conditions for the occurrence of mental depressions are determined. Such depressions will not thereby be shown to be illusory, and the word depression will still play a useful part in our vocabulary. The same argument can be applied to moral concepts such as right and wrong, just and unjust. As psychology and neurology advance we may come to modify our use of these terms – to apply them in more restricted situations perhaps – but it is unlikely that we shall dispense with them entirely.

Let us now look at the way causal explanations are used in science. Figure 3.1 shows a simple deductive system representing Galileo's theory of motion: it is an example used by Braithwaite in his book *Scientific*

High-level hypothesis I
Every body near the earth, falling freely, fall with an acceleration of $9.81 m/s^2$. Using the integral calculus:

$$\frac{d^2s}{dt^2} = 9.81 m/s^2$$

If $s = 0$ and $ds/dt = 0$ at $t = 0$

$$\frac{s}{[m]} = 4.9\frac{t^2}{[s^2]}$$

Lower-level hypothesis II
Every body starting from rest near the earth, falling freely, falls $4.9t^2$ metres in t seconds for all values of t

↓ By arithmetic

Lowest-level hypothesis III (a), (b), (c), etc.
   (a) Every body starting … freely for 1 second falls 4.9 metres
   (b) Every body starting … freely for 2 seconds falls 19.5 metres
   (c) and so on.

Figure 3.1: Simple deductive system due to Galileo. (Galileo actually used balls rolling down inclined planes, and a geometric argument instead of the integral calculus.)

Explanation, (C.U.P. 1953). The enunciation of the high-level hypothesis I is a scientific explanation of the events described by the lowest-level hypotheses III. This example exhibits most of the important features of a scientific explanation that we shall need to discuss.

(i) Verification of hypotheses

The high-level hypothesis is justified by testing instances of the lowest level hypotheses. We must note, however, that a finite number of verified instances can never prove a hypothesis to be true, whereas one instance to the contrary can prove it to be false. This is a consequence of the form which all scientific laws take. They are all of the form 'Every A is B', although A and B may be complicated statements such as: 'Every (system carried through a cycle) is (an instance of an event wherein the net work done by the system is proportional to the net heat transferred to the system)'. This is one way of expressing the First Law of Thermodynamics. Propositions of the form 'Some A's are B's' have the reverse asymmetry: no finite number of instances to the contrary can disprove them but only one instance of agreement proves them to be true. 'Some technologists are women' might be an appropriate example, and we certainly would not call this a scientific law.

A second point to note is that instances of hypothesis III(a), while evidence for hypothesis II, are also indirect evidence for the other lower-level hypotheses III(b), (c), etc. This is because all hypotheses III are logical consequences of hypothesis II. One of the main reasons for organising the theory into a deductive system is so that direct evidence for any lowest-level hypothesis can be indirect evidence for all the other lowest-level hypotheses.

Of course, most scientific theories have more than one highest level hypothesis. For example, when Galileo's theory is incorporated in Newton's, hypothesis I becomes deducible from Newton's laws of motion and his law of universal gravitation. Refutation of a lowest-level hypothesis will then not destroy the whole system, but will require at least one of the highest-level hypotheses to be modified. As to how to make the change, this is where the intuition and inspiration of an Einstein or a Max Planck are needed.

It should be clear from the foregoing that the essence of a scientific proposition is that it is falsifiable. It is most emphatically not a provable statement. It follows that scientists do not spend their time conducting experiment after experiment to make a hypothesis more certain and thereby turn it into a 'law'. Advances come by looking for a falsification – by seeking conditions under which the law does not hold. Major advances

are made only by changing a high-level hypothesis so that anomalous results can be explained. This enables the modified theory to embrace a wider range of phenomena. Those scientists hoping to make a major advance in their subject conduct experiments in unexplored situations hoping to find that the existing theory does not fit, and that they will be able to develop a theory that does.

Once a change in a high-level hypothesis has been accepted by the scientific fraternity, the whole system of ideas within which the related phenomena are studied undergoes a radical change. Certain properties of matter hitherto unknown or thought to be unimportant now become significant. What Kuhn[1] calls 'normal' science then takes over, and the ordinary practitioners in the field enthusiastically set about the task of measuring these properties. Much ingenuity goes into the design of apparatus for making the measurements and there is considerable satisfaction to be gained in the pursuit of a high order of accuracy. A good example of 'normal' science was the spate of work on the measurement of the properties of atomic nucleii once it was shown to be possible to induce nuclear reactions. A vast amount of work was involved in the measurement of the masses of nuclear particles, the nuclear cross-sections[2] of all the isotopes for a range of reactions, and the modes and rates of decay of radioactive isotopes. All these data were required if Planck's quantum theory and Einstein's mass-energy relation were to have useful predictive value. And the fact that all these data could be cross-checked to show an internal consistency provided support for the high-level hypotheses upon which quantum theory and the mass-energy relation were based.

(ii) Status of scientific laws

Perusal of a few autobiographies of great scientists leaves one in no doubt that high-level hypotheses are produced as an act of creation, springing into mind suddenly after a long period of worrying at the problem like a dog with a bone. They are not formed by some logical process of induction from an accumulation of results, which was the view taken by Francis Bacon. Until Karl Popper[3] had argued the case for the view of science presented here, philosophers of science spent much time and effort trying to solve the 'problem of induction'. How could a generalisation be arrived at logically from a finite number of instances? Why should the next instance follow the last? Reference to some principle such as the regularity of nature was no answer to the logical problem because it is itself a result of induction. The answer is in fact that science uses deductive systems of thought not induction.[4] In chapter 2 we said that Francis Bacon might be called the first philosopher of science: but we did not say he was correct in all his views, and in this respect he sent his successors off on a wild goose chase.

Once a hypothesis is accepted as a scientific law, this does not mean that it is regarded as an immutable truth about nature. Neither is it normally ever shown to be completely wrong. What happens is that it is shown to be applicable over a more limited range of conditions than was once thought. For example, Boyle's Law – that the pressure of a gas varies inversely with its volume when the temperature is constant – was found to be inexact when more accurate methods of measurement were employed, but to be more nearly 'obeyed' the lower the pressure and the higher the temperature at which the experiments were conducted. The reason that it is true only for a limiting case was satisfactorily explained when it was shown to be a predictable result of the kinetic theory of gases: that is, when it could be shown to be deducible by applying the ordinary laws of Newtonian mechanics to a model of gas conceived as a collection of molecules behaving like perfect billiard balls of negligible size.

To take another example, Newton's laws of mechanics were not replaced by Einstein's relativistic mechanics: they were subsumed in them. Newton's laws are still as applicable as ever to a wide range of phenomena, but they are not quite so universal as was first thought. When changes are made to a hypothesis at the head of a large deductive system like the science of mechanics, it is not surprising that there are very significant consequences. Thus mass was conserved under Newton whereas it is mutually convertible with energy under Einstein. Quite new things, such as nuclear physics, 'atom bombs', and nuclear power plant, suddenly become possible. It is indeed a brave man who says that something is impossible because of a scientific law: sooner or later he is likely to have to eat his words. For example, a great deal of modern physics depends upon the idea that the velocity of light (that is, radiation) is a universal constant. It is not impossible that eventually more astronomical data, collected by telescopes in space, will suggest that

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[1] T. Kuhn, *The Structure of Scientific Revolutions* (Chicago, 1962).

[2] A nuclear 'cross-section' is a measure of the probability that a particular nuclear reaction will take place.

[3] See B. Magee, *Popper* (Fontana/Collins, 1973).

[4] This is not to say that induction is useless: by looking at instances we can make such statements as 'most metals are ductile, so this new metal will probably be ductile'. Although they do not have the status of scientific laws, such generalisations are useful knowledge.

some events in the universe can be explained only by assuming that the velocity of light has varied over astronomically long stretches of time.

(iii) Contingent and necessary propositions

The next feature of Figure 3.1 which is worth a comment is the step from hypothesis I to hypothesis II. A scientific theory normally comprises two parts: (a) a set of propositions whose truth or falsity depends upon experiment – these are called *contingent* propositions; and (b) a set of propositions whose truth or falsity is largely a matter of logic – these are called *necessary* propositions. The latter is the mathematical part. (We say 'largely' a matter of logic because mathematics cannot in fact be reduced completely to logic. Russell and Whitehead attempted this in their *Principia Mathematica*, but failed. Since then one of the major achievements of mathematical philosophy has been to prove that this is a fruitless quest.) Fortunately a great deal of the mathematical part of a scientific theory can be dealt with separately, the resulting equations being fed into the system of contingent propositions at appropriate points. Figure 3.1 is dressed up in modern language, because Galileo preceded Newton and Liebnitz who introduced the integral calculus. Galileo accomplished the step from hypothesis I to hypothesis II by geometrical arguments which would be more difficult for the modern reader to follow. We have already noted in chapter 2 that the necessary mathematics has often been developed many years before it finds important applications in a scientific theory. Einstein, for example, had Riemann's non-Euclidean geometry (1854) and Ricci's tensor calculus (1887) ready to hand when developing general relativity (1916). Any Minister of Science should be prepared to finance mathematicians' research projects fifty years ahead of the scientists!

It is worth noting the essential difference between a mathematical theory and a scientific theory. A scientific deductive system can be extended virtually indefinitely in the upward direction so that the high-level hypotheses embrace wider and wider fields of experience. The process would be complete only if all the sciences could be shown to be part of one great deductive system. In contrast, mathematical deductive systems start at the top with initial axioms and can only be extended downwards. The validity of the axioms does not depend on the theorems deduced from them: it is the other way round.

(iv) The meaning of abstract scientific concepts

Although the simple example of Figure 3.1 does not show this, it is common knowledge that higher-level hypotheses invariably make use of theoretical concepts which are not observable by the senses – electrons, energy, entropy and so forth. Philosophers of science have now shown, fairly rigorously, that if these concepts were directly and completely definable in terms of observable things, the set of higher-level hypotheses containing them would become logically deducible from the lowest-level empirical generalisations which they purport to explain. They would then become simply another way of stating the same information and the theory would lose its power of being able to explain facts about new, hitherto unrelated, events. To have shown this is a major contribution of modern philosophy of science. It is now realised that the abstract concepts derive their meaning only by virtue of the part they play in the deductive system, and that there must be an element of vagueness in their definition. This is why, for example, it took so long for the early ideas about force, momentum and energy to be clarified. Initial clarification had to await the system of Newtonian mechanics. Indeed, owing to their indefiniteness, these concepts were still the subject of debate long after Newton, between men such as Helmholtz, Maxwell and Mach in the nineteenth century.

Because the meaning of scientific concepts is so closely bound up with the deductive system in which they arise, difficulties sometimes occur when one theory is reduced to another. One example is the difficulty of attaching a meaning to temperature – a concept in classical thermodynamics – when thinking in terms of statistical thermodynamics. It follows that it is most unlikely that theoretical concepts will make sense when used in entirely different contexts. Discussions of metaphysical or religious implications of scientific principles – such as the principle of increasing entropy – can be interesting, but the conclusions must be treated with reserve. For example, entropy is a concept arising from a study of finite systems and the principle could not logically be applied to the whole universe if one was arguing for a cosmology based on the continuous creation theory of matter.

It also follows that it makes little sense to ask such questions as 'Do electrons exist?' or 'Does entropy exist?'. For these concepts to serve their proper function in science, there is no necessity for there to be a one-to-one correspondence between them and things in the real world. In fact to regard these abstract concepts in such a way is to revert to the time of Francis Bacon. And to regard these concepts as in fact

the only reality, and the observable world as a mirage separating this reality from our minds, is to revert to Platonism. Plato thought that appearances were too often subject to illusion to be of importance, and that the essence of the world lay in the ideal, abstract, forms which the mind could deduce from these appearances.

(v) Science in perspective

Let us sum up this section on scientific explanation. Scientific explanations involve the establishment of general laws covering what were hitherto unconnected empirical events, and they enable predictions of future events to be made. In the early or 'natural-philosophy' stage of a science the laws are often merely classificatory. Even this is not a negligible step – to classify a whale as a mammal is to assert the generalisation that 'all baby whales are provided with milk by their mothers'. It singles out an important feature by which whales differ from fishes and enables us to predict that the next whale we meet will be a mammal. As science develops it explains low-level generalisations by deducing them from more general hypotheses which cover a wider range of experience. This organisation into a hierarchical system requires subtle deductive techniques, and these are provided by mathematics. The things with which the higher-level hypotheses are concerned often cease to be directly observable and become theoretical concepts which are meaningless out of the context of the deductive system in which they arise. We no longer pretend that our abstract concepts represent real things, and even explanatory models, like the kinetic theory of gases, become impossible to construct once we step into the heady realms of wave mechanics and quantum physics.

The reason why science is so successful is that most of the time it limits itself to problems which lend themselves to controlled experiment and which can be solved within the current framework of established scientific theory. But a word of warning is in order. There may still be those who are so impressed by the power of science, with its potential for ever-increasing knowledge which commands general agreement, that they dismiss other forms of knowledge and human activity as pre-scientific mumbo-jumbo. The reader is asked to reflect on the following two parables taken from Eddington's book *The Philosophy of Physical Science* (C.U.P. 1939).

The first parable is about an ichthyologist exploring the life of the ocean – he casts his net, analyses his catch, and pronounces his conclusion that no sea creature is smaller than two centimetres long. An onlooker points out that he is using a net of two centimetre mesh. But the ichthyologist, because he is a human being as well as a scientist, gets very cross and says that anything uncatchable by his net is not part of the kingdom of fishes, which has been defined as the theme of ichthyological knowledge, and is *ipso facto* outside the scope of such knowledge. In short he says 'What my net can't catch ain't fish'.

The second parable is an extension of the legend about Procrustes who stretched or chopped down his guests to fit the bed he had constructed for them. Eddington adds that perhaps we have not heard the rest of the story – how Procrustes measured his guests in the morning and wrote a learned paper for the Anthropological Society of America entitled 'On the Uniformity of Stature of Travellers'.

What the first parable suggests is that our sensory apparatus and the structure of our minds no matter how well supplemented by sophisticated measuring devices inevitably restrict what we can discover about the world. And the second parable suggests that the world we observe is modified by the mere act of our studying it. At the sub-atomic level this is true even of the most objective science – physics. Heisenberg's uncertainty principle is a formal expression of the fact (namely, the greater the accuracy with which we can define the position of a particle the greater the error in our knowledge of its velocity, or vice versa). Exactly what we know in science is completely mysterious: just as mysterious as that which the religious person believes he knows when he professes his creed. Just what *is* gravity, energy, an electron, and so on? Scientific explanations are justified because they help us make sense of the world around us and because they enable engineers and technologists to modify the world in ways which we hope will prove to be beneficial. If we judge science on the basis of its utility, rather than on whether it leads to some absolute 'truth', should we judge other forms of knowledge from a more elevated standpoint? If art and religion lead us to views of the world of human experience which are helpful, perhaps we should ask no more of them. Certainly we should not belittle them because they cannot be 'proved' and because they never command general agreement. It is naive to suggest that science is truth, art pure imagination, and religion mere myth. A more sophisticated view is expressed eloquently by Cassirer[5] in his book *Essay on Man*: 'In language, in religion, in art, in science, man can do no more than build up his own universe that enables him to understand and interpret, to articulate and organise, to synthesise and universalise, his human experience'.

[5]Ernst Cassirer, *Essay On Man* (Yale U.P., IQMH)

Because it may well have repercussions on our view of technological explanation, let us now make a diversion to consider the part explanation plays in historical studies. In what way does historical explanation differ from scientific explanation?

Historical explanation

The function of history is held to be 'to provide an understanding of the past in the light of the present, and of the present in the light of the past'. No mere chronology would fulfil this function of history. History must be an attempt to explain events, not just describe them.

The first point to note is that whereas the scientist works with effectively isolated systems, where the number of relevant variables is small and the events are repeatable, the historian deals with a total complex of events which has no definite beginning or end in time and which can never be repeated. The second point is that the subject matter of history are the acts of human beings who are commonly supposed to behave in a purposeful manner. It follows that historical explanations must have a teleological element even when expressed in causal language.

The explanation of a person's actions will involve at least two things: (a) reference to a purpose or intention, and (b) reference to previous events which gave rise to that purpose or intention. It is the group of previous events giving rise to the intention which is loosely called the cause of the person's action. But the same circumstances may give rise to different intentions in different people, and different circumstances may give rise to the same intentions in different people. There is, therefore, no inevitability about this kind of cause and effect. Furthermore, we are dealing with causal chains of events wherein alternative means may be used to achieve the same intention or end. It is clear that causal explanations in history will be quite different in kind from those in science.

Of course, for 'person' in what has been said, we may substitute words like government, nation or class. These are the abstract concepts used by historians. They are always given human attributes because they are groups of persons. The danger arises when this fact is forgotten and the concepts are treated as having a reality of their own quite apart from the people who comprise them. This is how the glorification of the state arises, often with the consequential death of millions of individuals.

How does the historian go about his job? The first thing he does is to group the possible causes of an event – into religious, economic, political, idealogical, personal or psychological causes and into long term and short term causes. He then tries to reduce them to some sort of order of importance, and sometimes to determine the 'ultimate' cause. Phrases like 'in the final analysis' and 'in the last resort' frequently appear in historians' writings. To do this selection, the historian must make use of some generalisations about the way human beings behave, both singly and in groups. These generalisations, however, are seldom explicitly stated, and instead the process is referred to as the 'exercise of historical judgement'. His difficulty is that he cannot merely use his experience of how human beings living now behave: he has to think himself into the minds of those living in the age he is studying. This is the reason why histories are rewritten time and time again. Historians have to adopt a kind of successive approximation – one assessment of the evidence will assist the next attempt, because the second historian is better able to appreciate the intellectual climate of the period.

Faced with all these difficulties of delineating either an area or period of study; of a multiplicity of causes; of the teleological element which is made worse by the ease with which human beings deceive themselves as to their motives for action – there can be no question of erecting hierarchical systematic theories or of making reliable predictions. The few historians who attempt this do not find favour with the majority. Arnold Toynbee, with his monumental thirteen-volume history of all known civilisations, is a recent example of a historian who attempted to fit history into a systematic theory. He introduced the concepts of 'challenge' and 'response' to provide an explanation for the rise and fall of civilisations. These are such broad and imprecise terms that they have little explanatory value.

Because we cannot expect anything like scientific verifiability, or much of predictive value, from historical explanation, do we then agree with Henry Ford that 'history is bunk'? Of course we do not. Most of our lives have to be run, and decisions taken, on the basis of the kind of intuitive judgements used by historians. The knowledge of human behaviour gained by the historians' work is part and parcel of the semi-conscious knowledge that we carry around in our minds and use in our daily lives. Certainly we act as though we believe human behaviour to be in principle understandable and to some extent predictable. If one day you were greeted by your wife at the breakfast table with black looks and a violent attack upon your mode of life,

you would not merely shrug this off as a convincing demonstration of the capriciousness and unpredictability of human nature. You would instead look for a cause and say something like: 'Oh dear, I have forgotten her birthday again.' This is the kind of thing historians are trying to do but on a rather larger scale.

Technological explanation

Explanations given in answer to questions about how a technical device works are largely teleological, that is, they are in terms of purpose. 'What is the flywheel for? – To reduce the fluctuations in torque which arise from the intermittent nature of the processes in a reciprocating engine.' 'Why is the spark initiated before the end of the compression stroke? – To allow for the delay in the ignition process.' Even though such questions must be asked and answered as a prelude to technological investigations, we are not here concerned with this relatively trivial kind of explanation. They are first-order explanations in the sphere of craft or technics.

Some examples of the sorts of situation in which mature technological explanations are called for are as follows.

(a) When a bridge collapses the engineer will be called upon to explain the failure: to determine the cause of the failure. The cause may turn out to be wholly technological, perhaps because the bridge is a new design sensitive to aerodynamic forces that had hitherto caused no problem, or it may turn out to be partly due to human error during construction.

(b) In the early days of engine development, trial-and-error experiments showed that ignition advance was necessary to make a spark-ignition engine run smoothly. Rule-of-thumb methods enabled this requirement to be incorporated in the design of such engines. When it became necessary to improve the engine efficiency – because of competition or rises in fuel cost – the technologist had to determine the causes of ignition delay so that he could find a way of controlling it. To do this he had to explain ignition delay in terms of the chemistry of the combustion process.

(c) Because of the high intensity of heat transfer in the core of a fast-breeder reactor, a liquid metal must be used as a coolant. If one used the same theory for calculating the required surface area that was developed from studies of heat transfer in air or water heaters, one would find that the rate of heat transfer obtained is not in accord with the theoretical predictions. An explanation would have to involve a detailed study of the way heat is transferred in boundary layers of fluid, which would in turn lead to a more comprehensive theory applicable to a wider range of fluids.

These three examples should serve to show that technological explanations are of a causal type: but are they causal in the way scientific explanations are causal, or are they perhaps closer to the causal explanations of history? The answer is that they vary across the whole spectrum between these two extremes.

Explanations of the causes of failure of any engineering construction – whether it be a bridge, a dam, or an aircraft – have many of the characteristics of an historical explanation. One would inevitably be distinguishing between immediate causes and ultimate causes, and between technological error and the human situations which might have contributed to that error. The immediate cause may be the failure of a structural component, but was the ultimate cause a simple error in the design calculations or was it an unusual set of conditions not taken into account by the theory? On the other hand, perhaps it was due to mismanagement of the process of construction or assembly. Going even further down the chain of circumstances, perhaps the ultimate cause was an inadequate system of engineering training. How far back in time one has to go before one can be said to have established the cause is somewhat arbitrary, and it depends upon the purpose of the enquiry. Are we merely trying to ensure that if we build an identical bridge/dam/aircraft again it will not fail, or are we trying to ensure that any subsequent design of a similar but not identical kind will not fail?

Turning now to consider explanations arising from such problems as (b) and (c), that is, the causes of ignition delay and the failure to predict heat transfer rates when using liquid metals, it is clear that they will be at the science end of the spectrum. Solutions of these problems involve the establishment of technological theories: of chemical kinetics in the case of problem (b) and of convective heat transfer in problem (c). Both theories have been built up steadily from a study of many different but related problems in each field. To see how technological theory differs from scientific theory, let us consider a concrete example wherein

both types are involved and interact with each other: we will contrast thermodynamics with its technological counterpart 'engineering thermodynamics'[6].

(i) Thermodynamics

The science of thermodynamics arose in answer to problems posed by the development of heat engines in the eighteenth century. A heat engine is a device for converting heat continuously into mechanical work. Originally the heat was provided by the combustion of wood or coal, but soon engines were developed which used oil and gas as the fuel and nowadays the heat source might be a nuclear reactor. It is not surprising that the science of thermodynamics underpins the technologies associated with power plant: yet as we shall see, it does not by itself carry us very far.

state described by values of properties:
    volume
    pressure
    temperature

1st law
For a cycle: $Q \propto W$

deduction

There exists a property, E, such that $\Delta E = Q - W$ for any process

(a)

2nd law
For a cycle: $Q_R > 0$

All ideal (reversible) engines with source at t_s and   hwffactah sink at at t_R have the same efficiency

There exists an absolute temperature scale, T

For a cycle: $Q/T \leq 0$ $\begin{cases} (Q/T)_{rev} = 0 \\ (Q/T)_{irrev} < 0 \end{cases}$
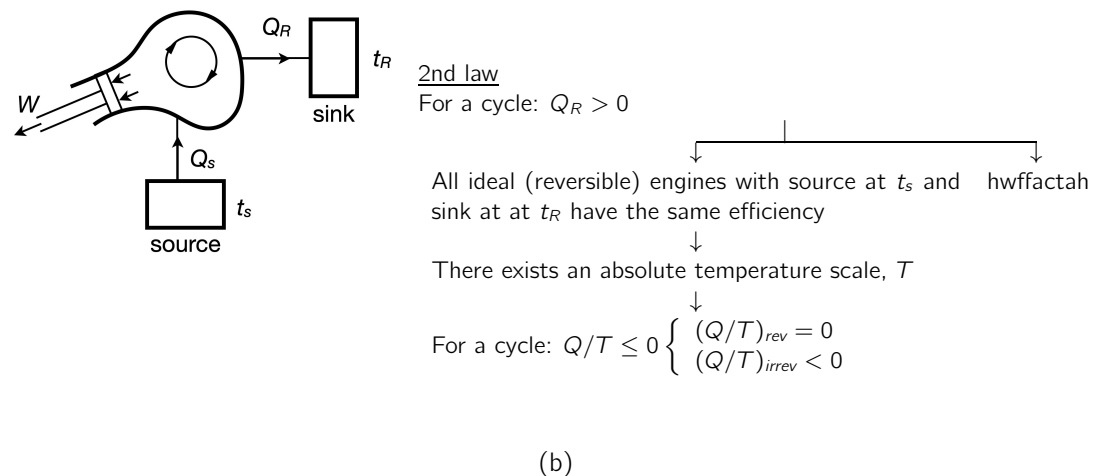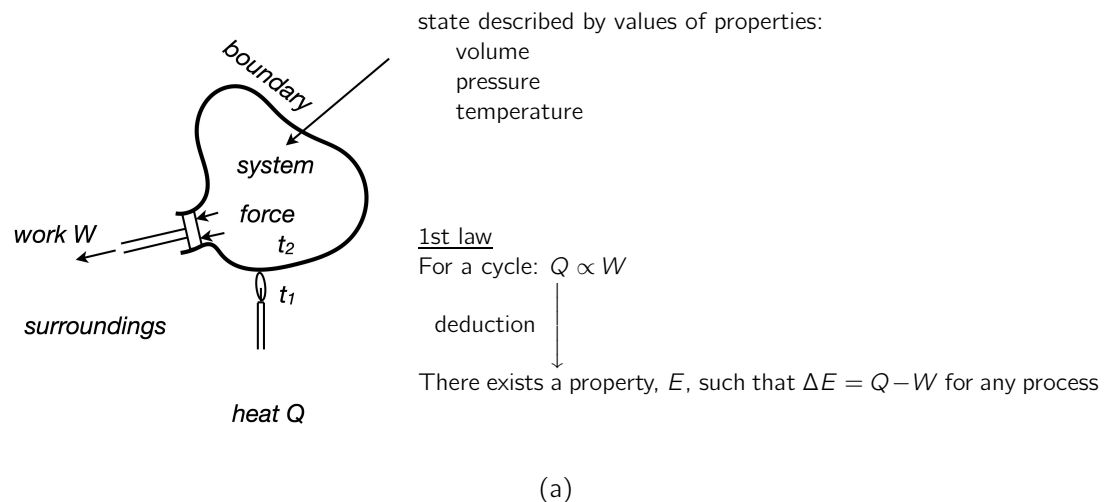
(b)

Figure 3.2: Logical structure of thermodynamics

    Figure 3.2(a) and (b) depicts the logical structure of classical thermodynamics based on the First and Second Laws of Thermodynamics. Thermodynamics deals with phenomena which arise when a system (any collection of matter) interacts with its surroundings due to the movement of a force at the boundary, or due to the difference in temperature $(t_1 - t_2)$ between the system and surroundings (see Figure 3.2(a)). In the former case work (W) is said to be done, and in the second case heat (Q) is said to be transferred. The state of the system at any instant is described by the value of its properties – volume, pressure, temperature, say. Experiments on a variety of systems have shown that when the system is taken through a cyclic process, so that it is brought back to its original state and all its properties have their original values, the net quantity of heat transferred to the system is proportional to the net work done by the system. If we postulate that this is true for all imaginable systems, we have what is called the First Law of Thermodynamics. We are

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[6]The non-technical reader may wish to skip the remainder of this section.

satisfied with the hypothesis because no experiment has ever refuted it, nor refuted any of the consequences which follow logically from it.

The most important consequence of the First Law is the deduction (by a very simple mathematical argument) of the existence of a property of the system which we call the 'internal energy'(E). It is no less a property because it is unobservable directly by the senses: what is important is that a change in its value depends only on the end states and not upon the process joining the states. Having established the existence of this property, it is possible to define what is meant by work and heat more clearly. These are now seen to be names for different ways in which energy is transferred between the system and its surroundings. Furthermore we can now write down an equation which applies to any process – not just cyclic processes – and this is referred to as the energy equation, namely $Q = \Delta E + W$.

Reverting to the cyclic case, and referring now to Figure 3.2(b), we see that what we have is an engine work being delivered to the surroundings continuously by a system undergoing a series of cyclic processes while exchanging heat with a source and sink of energy. We see directly from the First Law that no system can be devised which will produce work continuously without energy being supplied, that is, if $Q = 0$ then $W = 0$. But an enormous reservoir of heat exists in the atmosphere and ocean. Why is it not possible to power our ships by tapping such sources of heat? It is the Second Law of Thermodynamics which tells us that this very valuable type of perpetual motion machine is impossible. What the Second Law states, in effect, is that during any cycle some heat must be rejected to the surroundings, that is, $Q_R > 0$. Since there is no natural sink of heat at a lower temperature than the ocean, our highly desirable engine is impossible. Furthermore, since we can never convert all the heat supplied (Q_s) into work, our engines can never have an efficiency ($W/Q)_s$ of 100 per cent. An immediate consequence is that although heat and work are both transfers of energy they are not quite mutually convertible: a source of work can always be completely transformed into heat but a source of heat cannot be completely converted into work. Thus work is a more valuable form of energy transfer than heat.

Oddly enough, from this rather negative statement which we call the Second Law, a large number of most important and positive consequences follow as logical deductions. The deduction written as 'hwffactah' in Figure 3.2(b) is not a Welsh village; it is simply short for 'heat won't flow from a cooler to a hotter', a result well publicised by Flanders and Swann. This is often used as a statement of the Second Law and the two statements are in fact interchangeable. The second deduction – known as Carnot's principle – is a statement about the efficiencies of ideal or 'reversible' engines, which apparently all have the same efficiency when operating between the same source and sink of heat. Furthermore, since these engines may differ in every respect other than in the temperatures of their source and sink, the efficiency must depend only on these temperatures.

At this point it is necessary to say something about the notion of *reversibility*, which is a concept central to classical thermodynamics. Consider a weight being lifted by a rope over a pulley. With a frictionless pulley, the work done on the system in raising the weight is equal to the gain in potential energy of the weight. If the weight is allowed to return to its original position, the system will do as much work as was done on the system in the first place. The original process was completely reversible, because both the system and its surroundings can be restored to their original states. Now consider what happens if there is friction in the pulley bearing. The work required to lift the weight is now greater than the increase in potential energy, the difference appearing as an increase in internal energy in the bearing. Furthermore, when the weight is lowered to its original level all the potential energy is not converted into work: again there is an increase in internal energy in the bearing. The system can be restored to its original state by allowing heat to be transferred from the bearing to the surroundings, but the surroundings cannot be restored to their original state. In the surroundings there is a deficiency of work and a surplus of heat, and the Second Law implies that the heat can never be completely converted to work. The original process in this case must have been irreversible. No work was wasted in the reversible process, whereas some of it was wasted in the irreversible process. Any irreversibility always means that some capacity for producing work is irretrievably lost, and that the universe can never be quite the same again after it has occurred. When heat is transferred by virtue of a finite temperature difference, this too can be shown to be an irreversible process. Since real processes always involve friction and/or heat transfer across a finite temperature difference, all real processes are irreversible processes.

Reverting once more to the deductive theory, Carnot's principle enables us to define an absolute scale of temperature: a scale which is quite independent of the behaviour of any thermometric substance such as mercury in a glass tube or the pair of metals used in a thermocouple. Temperature on this fundamental scale is denoted by T. It is then possible to show that the quantity of heat divided by the temperature at

which it is transferred to the system (Q/T) has a special significance. Summing up all such quantities for a complete cycle we can show that it is either zero (if the cycle is composed of reversible processes) or negative (if there is any irreversibility). We are then able to deduce that there must exist another property of the system, which we call the entropy (S) and which satisfies the equation $\Delta S = (Q/T)_{rev}$. That is, if we imagine a reversible process to carry the system from one state to another and calculate the ratio Q/T, we obtain something which is quite independent of the process and depends only on the end states. This 'something' is the change in entropy of the system. It is not too much to say that it is the existence of the property entropy which makes thermodynamics such a powerful tool for the analysis of all phenomena involving heat and temperature. Finally, we can show that for any isolated system (that is, no heat transfer to or from it), there must be an increase in entropy if there is any irreversibility present, or no change in entropy if the process is reversible. This 'principle of increasing entropy' tells us the direction in which real processes must proceed; in some way it must therefore be associated with the directional property of time and the notions of past, present and future.

It is an empirical fact that the state of a simple system consisting of a gas, vapour or liquid is fixed when any pair of independent properties are specified. This implies that any third property is some function of the chosen pair. Thus $p = f(V, T)$, $S = \varphi(V, T)$ and so on. The laws of thermodynamics place a restriction on the form of these functions in the sense that once the p–V–T relation is specified the other property relations must take a particular form. Although there will be constants in the equations whose values differ for different substances and which must be found by experiment, thermodynamics enables the results of one set of experiments to be correlated with those of another. Once these property relations have been established, it is then possible to calculate the heat and work transfers in any specified process provided that it can be regarded as a reversible process.

What we have done here is outline the basic principles of thermodynamics up to the point where the scientist proceeds to apply them to a variety of phenomena concerned with chemical reactions, surface films, thermocouples, electrochemistry, low-temperature physics and a host of others unrelated to the design of power plant. The scientist uses thermodynamics in his continuous pursuit of knowledge about the behaviour of matter at the molecular, atomic and subatomic level, often using statistical thermodynamics rather than the classical thermodynamics outlined here. Classical thermodynamics describes systems in terms of macroscopic properties: properties of the system as a whole like pressure and volume. Statistical thermodynamics tries to predict the macroscopic phenomena in terms of the microscopic behaviour of the constituent particles. On this view, for example, pressure is the average rate of change of momentum due to molecular impacts on unit area, and temperature is a measure of the average kinetic energy of the molecules. Here the scientist is creating a model of the system to enable thermodynamics to be explained in terms of mechanics. It is important to appreciate the secondary importance of the model. A change in our ideas about the microscopic nature of matter might lead to a different model, but it must still be capable of predicting the results of classical thermodynamics.

(ii) Engineering thermodynamics

We have said that thermodynamics is concerned with the relationship between work and heat and the properties of systems. The scientist, however, is not in the least interested in the details of how work and heat are transferred in practical engineering plant: in reciprocating and rotary machines, in boilers and condensers, and so on. At this point he hands over to the engineer/technologist, who has systematised knowledge of such matters in a subject called 'engineering thermodynamics'. Let us now look at the chief characteristics of this subject.

The first point to note is that while classical thermodynamics was built up from a study of what happens when a fixed mass of substance undergoes a change of state, engineering thermodynamics places much more emphasis on what happens when a fluid flows through a piece of equipment. It is the steady-flow energy equation which is the basic tool of analysis and not the ordinary energy equation of classical thermodynamics. It follows that engineering thermodynamics makes use of knowledge about the flow of fluids which is itself systematised in the subject of fluid mechanics.

While thermodynamics enables us to calculate the quantities of work and heat transferred in reversible processes, the engineer/technologist is interested in predicting what happens in real, *irreversible*, processes. Viscous friction is always present, and heat is transferred across an appreciable temperature difference to ensure that the plant is of economic size. Consequently he has to build up his knowledge of the way work and heat are transferred in practice by performing experiments. Such experiments might, for example, take

(a)

$$\frac{s}{ut} = 1 + \frac{1}{2}\left(\frac{at}{u}\right)$$

(b)
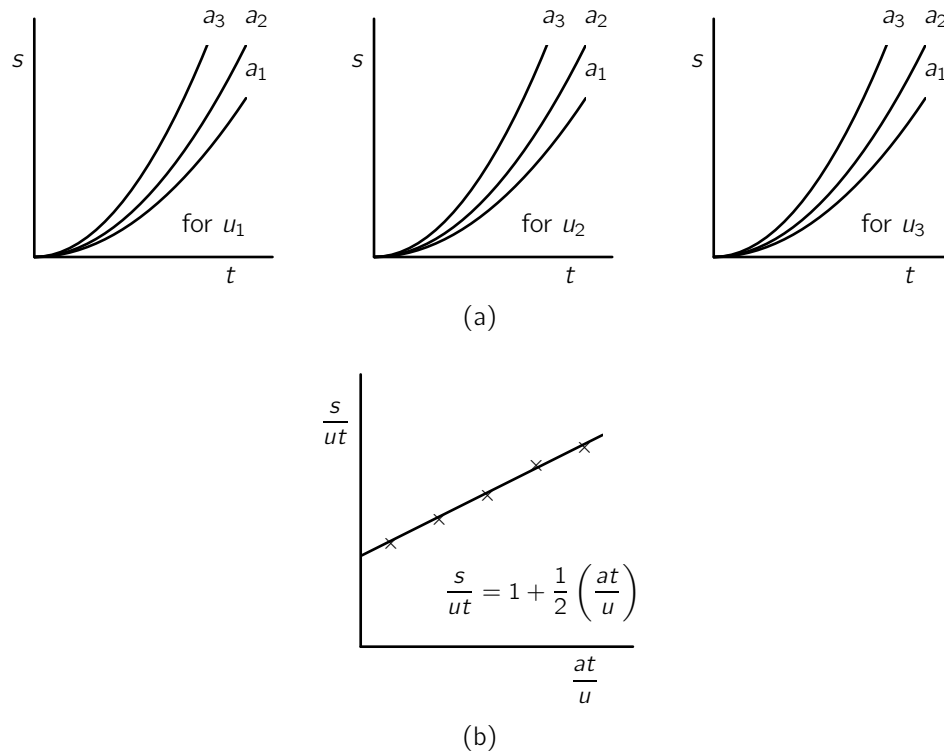
Figure 3.3: Graphical representation of $s = ut + at^2/2$

the form of measuring the way different fluids flow around turbine blades of various shapes in a special type of wind tunnel; or of measuring the rate of heat transfer from a fluid to a surface of given shape over ranges of values of velocity, density, viscosity and thermal conductivity of the fluid. The empirical theories developed enable him to determine the size and shape of a piece of equipment to perform a specified duty, or to predict the performance of the design when it is called upon to function under other operating conditions. Such calculations are referred to as 'design-point calculations' and 'part-load calculations' respectively.

The theories are characterised by the use of a multiplicity of empirical coefficients or process efficiencies, which are necessary because the engineer/technologist is dealing with real, irreversible, processes. Much use is made of so-called laws – such as Fourier's law of heat conduction and Newton's law of viscosity – which take the form of a proportionality between a quantity transferred in an irreversible process and the gradient of a property which is the driving force for the transfer. In the two examples mentioned the gradients are those of temperature and velocity respectively, and the constants of proportionality are the thermal conductivity and viscosity. Such laws are approximate empirical relations whose accuracy can be determined by experiment. Their inaccuracy is manifested by the fact that the 'constants of proportionality' are not in fact constant but vary with the conditions of the experiment. It follows that these laws are quite different in kind from the Laws of Thermodynamics which are fundamental hypotheses at the head of a deductive system on which the science is based, and which can only be shown to be true, false, or part of an even broader generalisation about nature.

One other noticeable feature of the theories produced by the technologist is the frequent use made of dimensionless groups of variables. The Mach number, Reynolds number, and Nusselt number are well-known examples. This procedure is made necessary by the very large number of variables affecting the phenomenon under investigation. Only by grouping these variables sensibly can we hope to reduce the results to manageable proportions and bring order out of chaos. A very simple example will illustrate the principle involved. Figure 3.3(a) shows a series of graphs representing one of Newton's equations of motion expressing the distance moved s as a function of initial velocity u, acceleration a and time t. Knowing the values of u, a and t, the distance s can be obtained from the graphs. Note that a very large number of experiments would be required to establish the curves if the equation was unknown. In Figure 3.3(b) the equation appears in non-dimensional form, (s/ut) and (at/u) being pure numbers. Only *one* curve on *one* graph is necessary to convey the same information as Figure 3.3(a): again, if u, a and t are known, (s/ut)

can be read from the graph and s calculated. Even more important, far fewer experiments need be performed to establish the information. All that is required is that an adequate range of (at/u) is covered, there being no need to cover wide ranges of a, t, and u separately.

The reader might well ask what is the point of doing this when it is just as easy to use the equation directly? The answer is that with the aid of the technique of *dimensional analysis* it is possible to arrive at suitable dimensionless groups when no simple equation exists. And this is the situation in which the engineer/technologist usually finds himself. Dimensional analysis will tell him that D_1 is a function of D_2 and D_3 say, where the D's are the relevant dimensionless groups of variables. His experiments will be directed towards determining the function. For example, he may find that he can express the function as $D_1 = A(D_2)^m(D_3)^n$, where a, m and n are constants determined by the experiments. He is then said to have established an *empirical equation*. The range of values of D_2 and D_3 covered by his experiments will be carefully specified. Serious errors can result from using such equations to find the dependent variable in the group D_1 when D_2 and D_3 lie outside the specified range.

There is one other limitation which must be noted. One of the variables will be a dimension (for example, length or diameter) which is characteristic of the geometry of the system under investigation. The equation can be applied only to geometrically similar systems. This is no drawback in practice because the experiments will have been performed on a scale model of the real system. One powerful advantage of dimensional analysis lies in the fact that one of the groups often consists of fluid properties (for example, specific heat, viscosity, thermal conductivity and so on). This means that experiments can be performed using any convenient fluid, so long as the range of values of that dimensionless group is the same for both the fluid used in the experiments and the fluid used in the actual plant.

One might argue that the empirical equations used by the technologist are no more than sophisticated rules-of-thumb. This is not true, however, because there are unifying principles within each class of phenomena. Side-by-side with the empirical equations there are theoretical equations derived from idealised models of the phenomena: for example, the equations expressing the behaviour of a non-viscous fluid, or the behaviour of a perfectly elastic solid. These fundamental equations tell us which are likely to be the important variables in a given situation, and help us decide on the most fruitful experiments to perform. Technological theories are much more than sets of rules-of-thumb.

We have already stressed the teleological distinction between science and technology, and the fact that the technologist aims at providing sufficient information to enable the engineer to design a piece of equipment to serve a given purpose. The engineer must call on the work of many technologists even within a restricted range of endeavour: let us say in power plant design. For example, the gas turbine engine designer must call on the specialised knowledge of the combustion technologist, the aerodynamicist, the metallurgist, the materials scientist, the stress analyst, the control-system technologist, and many others involved with the process of manufacture and production of components including those concerned with industrial relations and the economics of the applications of the engine. All of these individual technologies have systematic bodies of knowledge associated with them. Some are related to a basic science which provides the necessary fundamental concepts, as combustion technology depends upon chemistry for example. Others are based on theories developed solely from a study of engineering plant, such as control-system technology: in this case it is mechanics and mathematics which provide the unifying concepts. In all cases the test of a satisfactory theory is that it should enable the engineer to design a piece of equipment which will give the performance required of it. If an addition to a technological theory makes the whole theoretical structure more widely applicable this is a welcome added bonus, but it is not the prime object of the work as it is in science.

Any engineer reading this section will have been struck by the somewhat artificial way in which the term technology has sometimes been used. It is time that we clarified the distinction drawn between engineering and technology in chapter 1, and introduced a third term in common use, namely, 'engineering science.' The remainder of this chapter will be devoted to a discussion of these matters.

Engineering, technology and engineering science

The word 'engineering' has the form of a verb, and rightly so because it refers to an activity. From what was said about the origin of the term engineer in chapter 1, and the description by Vetruvius of the qualities required of an engineer (see chapter 2), it should be clear that engineering refers to the practice of organising the design and construction of any artifice which transforms the physical world around us to meet some recognised need. The main ways in which we do this were listed in chapter 1: we do it by increasing the

efficiency (a) of our body, (b) of our senses, and (c) of our intellect. We have said that an engineer is likely to make use of a number of different technologies in pursuit of his aim. How might technologies be classified? One possibility is via the avenues through which we meet our needs. We would then have as examples of avenue (a), machine-tool technology, automobile technology, marine technology etc.; as examples of avenue (b), various instrument technologies, metrology and so on; and as examples of avenue (c), the technologies of printing, photography, and computing. We might refer to these collectively as *product technologies*. In practice we also have a number of technologies based on the *materials* needed for these product technologies, namely, iron, steel, oil, coal, rubber, ceramics, etc. Used in either way, technology is a word signifying a body of knowledge associated with a particular industrial activity.

We have also said that technologies are more than mere collections of sophisticated rules-of-thumb. Craft and technics are certainly based on rules-of-thumb: for example, 'to anneal copper, heat to 600°C and cool slowly in air', or 'to harden steel, heat to 900°C and quench in oil'. But once research has explained why such rules are effective by discovering unifying principles for a limited class of phenomena, they become well-grounded, rational rules and a technology can be said to have appeared. When information covering a broader class of phenomena can be organised into a comprehensive body of theory using unifying concepts, principles and formulae, something else is born. To carry our example further, when rules-of-thumb such as 'to fire the glaze, heat to a temperature of 1600°C', and 'to temper glass, heat to 600°C and cool the surface rapidly', can also be encompassed by the theory, the subject 'properties of materials' appears on the scene. In other words some common principles have been found within the technologies of metals, ceramics, plastics and so on.

There are in fact a large number of such bodies of knowledge which are concerned with fundamental principles underpinning various technologies. In addition to 'properties of materials' we have such subjects as strength of materials, fluid mechanics, engineering thermodynamics, mechanics of machines and so on. These are what are referred to as the *engineering sciences*. They may or may not be closely linked to associated sciences. We have seen that engineering thermodynamics is closely linked with the science of thermodynamics, but so far there is very little in common between the engineering science of strength of materials based on a study of the macroscopic behaviour of materials, and the information which the solid-state physicist has gained from his study of material behaviour at the microscopic level. The engineer's education and training involves firstly the mastery of an appropriate group of engineering sciences – under the headings aeronautical, civil, electrical, mechanical, chemical and so on – coupled with training in communication via engineering drawing. And secondly, it involves the mastery of a technology through practical experience in a chosen industry coupled with specialised postgraduate courses which may cover technical or managerial topics. Figure 3.4 is one way of depicting the classification of technical knowledge outlined here.

Whether or not they are closely linked with a particular science, the engineering sciences are so called because they have some of the characteristics of science. For example, the expansion of knowledge is self-generating because the formation and application of theories throw up new questions, so stimulating further research. Although the research is often undertaken to support a new technology – offshore mining technology say – it is sometimes pursued as an end in itself just as is science proper. The former type of research is undertaken mainly in industrial or governmental laboratories whereas the latter more often takes place in universities.

It follows that our knowledge of engineering science is cumulative, grows continuously, and is never-ending. Product technologies, on the other hand, can remain virtually unchanged for decades, and fall into disuse when some totally different technology arises which serves the particular need rather better. 'Better' might mean: more cheaply in terms of labour cost, material cost or energy cost; or having a less deleterious effect on the environment and health of the population. A change of technology is usually associated with an invention rather than research, although supporting research may be needed to bring the invention to fruition. No amount of money poured into research laboratories can bypass the need for individuals with original ideas. This is sometimes forgotten by those who call for more money to be spent on so-called 'alternative' energy programmes based on renewable resources. The point has been expressed strongly by Lord Zuckerman: 'A cure for cancer will be discovered only when some new genius reaches a new understanding; one day perhaps another genius will discover how to tame the processes of nuclear fusion; and in the fullness of time maybe someone will develop a simple effective device which will allow us to see in the dark. But none of these things will happen except as spontaneously creative acts of particular gifted individuals.'

Engineering sciences differ from science proper in the way in which it is appropriate to ask whether their theories are true or false. One should ask of the engineering sciences only that they be adequate for the underpinning of our technologies. A theory can be of great practical use for design purposes, yet inadequate
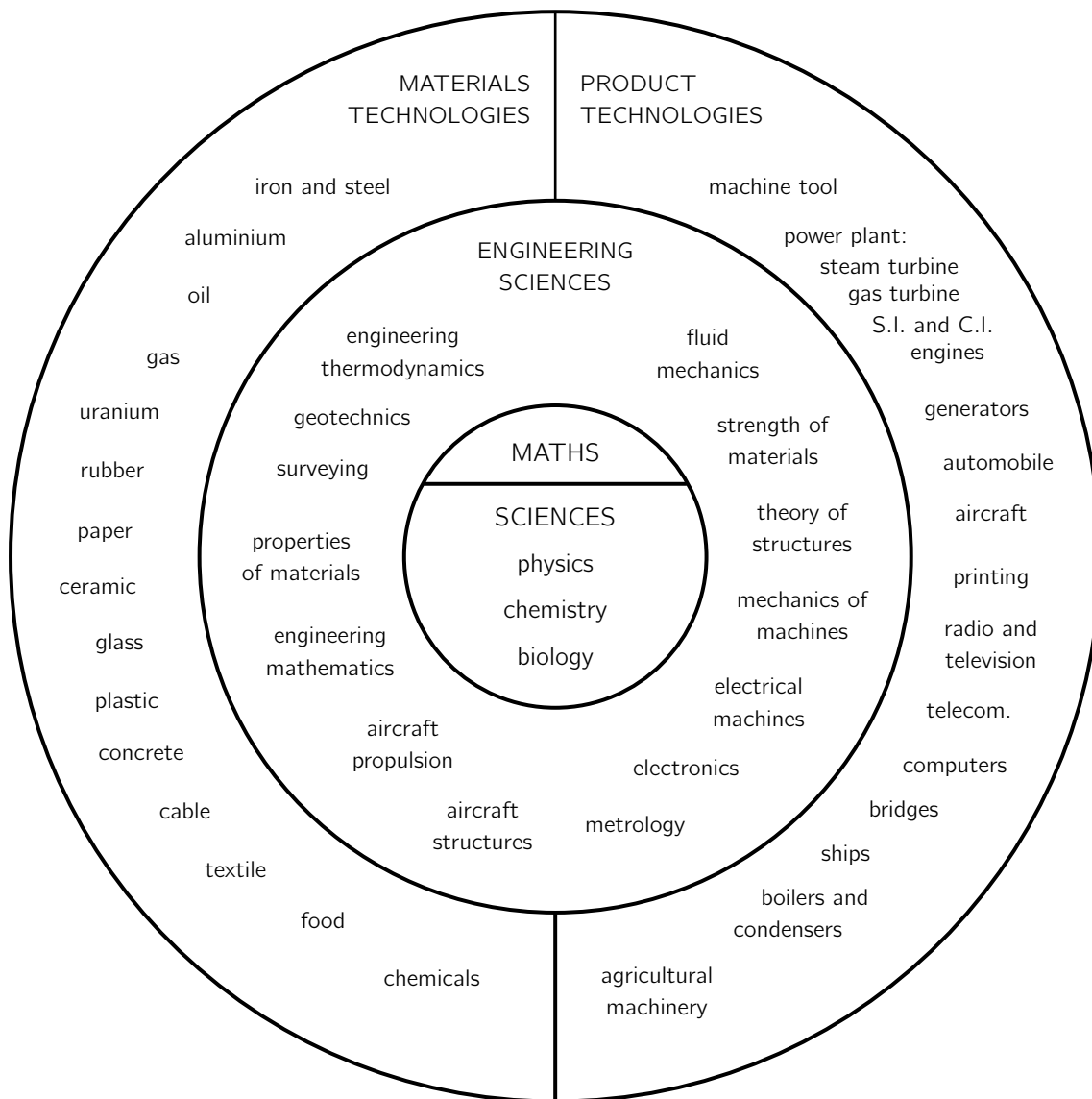
Figure 3.4: Classification of technical knowledge. (The lists are indicative, not exhaustive.)

from a scientific point of view. For example, nuclear power stations are designed using a theory called 'reactor physics' which is based on a rather crude model of the atom. No one would suggest that the fact that a nuclear power station works, in any way validates that model as the best representation of an atom which science can formulate. A much more elaborate model is required to explain the results of modern nuclear physics. Similarly, much optical equipment is designed on the basis of the corpuscular theory of light: this does not invalidate the more comprehensive wave theory. Successful practice, that is, a successful application of a theory, does not by itself validate the theory.

There is another rather obvious difference between engineering science and science, which is related to the difference just discussed. One cannot 'do' science without 'knowing' science because science is knowledge. One can, however, 'do' engineering or technology without knowing engineering science because engineering and technology are about making things. Practical knowledge can co-exist with theoretical ignorance, and theoretical knowledge with practical ineptitude. For this reason alone, practice cannot be an adequate test of the 'truth' of a theory.

We opened this chapter by referring to the different aims of the scientist and technologist, and stated baldly that one consequence is that technological explanation involves a level of approximation unacceptable in science. We can now see how this arises. High accuracy is often required in science because small differences can decide which of two competing theories should be preferred. Such accuracy is achievable

because the scientist is usually working with a well-defined system having a limited number of variables, under carefully controlled conditions. The technologist, on the other hand, must often work with apparatus which only approximately models the full-scale device. The theories which he develops to explain the results of his experiments, and to enable predictions to be made, will strictly apply only to the structures or fluid flows which he used in his apparatus. He will not be certain that his results can be extrapolated to the full scale, nor will he know with any accuracy the conditions under which the full-scale device will have to operate in practice. It is for these reasons that an engineer has to introduce safety factors in his design calculations. He will also build and test a full-scale prototype whenever possible. It follows that the technologist is seldom seeking the same experimental accuracy as the scientist.

There is another consequence of the teleological difference between science and technology. We have seen that in one sense science progresses by virtue of discovering circumstances in which a hitherto acceptable hypothesis is falsified, and that scientists actively pursue this situation. Because of the catastrophic consequences of engineering failures – whether it be human catastrophe for the customer or economic catastrophe for the firm – engineers and technologists must try to avoid falsification of their theories. Their aim is to undertake sufficient research on a laboratory scale to extend the theories so that they cover the foreseeable changes in the variables called for by a new conception. The scientist seeks revolutionary change – for which he may receive a Nobel Prize. The engineer too seeks revolutionary conceptions by which he can make his name, but he knows his ideas will not be taken up unless they can be realised using a level of technology not far removed from the existing level. Furthermore he is very conscious of the fact that his failures are immediately drawn to the attention of the public by the media, whereas the failures of science are more often known only to colleagues in the laboratory.

Certainly revolutionary changes do arise as a result of accidental failures in engineering constructions – the discoveries of the phenomena of fatigue, creep and brittle fracture in materials were made in this way – but they represent a failure, not a success, for technology. Nowadays revolutionary changes in technology arise from another source also – from new scientific discoveries. But these one might say are spin-offs from the successes of science. Bearing in mind the restrictions placed upon engineers and technologists by economics, health and safety regulations, pollution controls, labour relations and so on, there is little doubt that the normal successful path for technology is one of evolution rather than revolution. The question of how technological innovation arises is the main subject of the next chapter.

Chapter 4

Creativity and Engineering Design

Engineering as an art?; the creative process; engineering design.

From what has been said of the nature of scientific explanation in the last chapter it would seem reasonable to depict the development of science as in figure 4.1(a). Of course, this is merely a formal scheme and no one would pretend that science actually progresses in such a tidy manner. There is no indication, for example, of the long and often bitter controversies that ensue before a new hypothesis is accepted. Bearing in mind that the aim of engineering is the production of some artefact, one may depict the development of engineering as in figure 4.1(b). Elements in this scheme which are associated with the design process deserve special attention because design plays such a central role in engineering. In this context it will be necessary to discuss the nature of creativity. Most of this chapter is devoted to these matters.

The reader will note that the beginning and end of the engineering scheme is denoted by the phrase 'state of the art': a colloquialism often used by engineers. Engineers frequently present papers at conferences in which they claim to be outlining the current state of the art in their field. It may be of interest to examine the phrase to see if it means anything more than 'state of technology'. Again, it is often said that engineering is as much an art as a science. We ended chapter 2, however, by suggesting that both science and engineering differ markedly from the arts. There is clearly some confusion here that deserves examination. We have discussed engineering *vis-à-vis* science at some length, and it would not be entirely out of place to examine its status *vis-à-vis* art. To do so will be consistent with our broad aim of finding the place engineering occupies within the whole spectrum of knowledge.

Engineering as an art?

The Greeks and Romans had no word for 'art' as it is used in the modern world. To them it meant a craft or specialised skill – whether carpentry, surgery, painting or sculpture. And so it remained until after the Renaissance. It was not until the eighteenth century that people began to make a distinction between 'fine arts' and 'useful arts', and between 'artists' and 'craftsmen'. Only then did writers on aesthetics appear and begin to use the collective noun 'art' as a generalised concept. It is this last use of the word art that we must examine, because we must assume that when engineers speak of their activity as an art they are not just meaning that it is a craft, either 'useful' or 'fine'. That engineering involves the use of crafts is too obvious for engineers to point out, and we have already argued that engineering is much more than craft. Our starting point will be to see what is meant by 'art' and to see how the concept can be distinguished from craft.

Craft is the power to produce a preconceived result by consciously controlled action: the craftsman always knows what he wants to make in advance. Furthermore it is always possible to distinguish between the raw material and the product, and there is a hierarchical relation between various crafts in the sense that the finished product of one often becomes the raw material of another, for example, spinning-weaving-tailoring or steel making-forging-machining-fitting. Finally, with any craft it is always possible to differentiate between the means (tools) and the end (artefact). All crafts have most or all of these characteristics. Do we find these same characteristics in the arts, or is there something about 'art' which distinguishes it from craft?

Firstly, it can be argued that in many cases a work of art is not preconceived in the mind of the artist, and that the final form which emerges is as much a surprise to the conscious mind of the artist as to his audience. What an artist wants to say is not often clearly and consciously present as an end for which he merely has to devise a means of expression. What he wants to say becomes clear only as the poem takes shape in his mind, as the paint is applied to the canvas, or the clay takes shape in his hands. Certainly there are many cases where the poet, sculptor or composer is meeting a broadly specified need – to commemorate a royal event, to fill a niche in a public building, or to provide the incidental music for a film – but on the whole most people would say that the more detailed the specification the less the product is likely to be regarded as a work of art and the more it is likely to be regarded simply as an exercise of the artist's skill or craft. This may be a romantic view of art to be taken with a pinch of salt, but what one can say at the very least is that unplanned works of art are possible whereas an unplanned product of a craft is a contradiction in terms.

We next turn to the distinction in any craft between raw material and product, for example, between the wood and the table produced from it, or between the ingredients and alloy produced by a metallurgical process. It cannot be said that there is the same sort of distinction in a work of art. One cannot say that a poem is made of words, that a piece of music is made of notes, or that a painting is made of layers of paint, in quite the same way that an artefact is made from its raw material. One could say this kind of thing about the construction of crosswords, the formation of a musical scale, and the 'painting by numbers' sets offered as Christmas presents to children, but none of these activities could lead to a work of art. Evidently there is something subtle about the relationship between vehicle and final work of art which is not present in craft. There is little doubt that this subtle something is an emotional experience which the artist is trying to understand, and express or capture in some way.

Consider a portrait painter. If he uses his skill merely to satisfy his patron's desire for a likeness he will not produce a work of art, and indeed an undoctored photograph would serve the purpose rather better. What the great portrait painter tries to do is to invoke a feeling in a person looking at the painting that he is in the presence of the sitter. To do this the artist may have to emphasise some characteristics and play down others. What he is after is not a literal likeness but an emotional likeness. Anyone doubting this is asked to recall the portraits of Somerset Maugham and Winston Churchill by Graham Sutherland. Or consider the painter more generally: there can be no doubt that his visual sense is much more acute than that of the general public and that this ability to see form and colour is enhanced by his practice of painting. As a result, his observation of an object or scene can elicit a personal emotional experience denied to the casual observer of that object or scene, and it is this emotional experience which the artist hopes will be conveyed by his painting.

The third characteristic of craft which we noted was that the product of one craft could become the raw material of another. Does art have this hierarchical characteristic? When a poet writes verse which a composer sets to music, the verse is in no sense the raw material of the music. What happens here is a blending of two art forms into a third – in this example a song or opera – and the final result could be a work of art of some significance even though the individual contributions of verse and music taken separately are rather ordinary. A scientific analogy might be the difference between a mixture and a chemical compound. The latter has quite different properties from those of its constituents, whereas the former has not.

Finally, we turn to the distinction between means and end which is always characteristic of a craft. The writing of a poem, novel or play certainly does not involve the use of a tool or its equivalent, except for the purpose of writing down the result (that is, pen and paper). A composer of music usually finds an instrument of great assistance but it is not essential: Beethoven still composed after becoming deaf. On the other hand, painting and sculpture does involve the use of tools, and essentially so because the artist thinks by feedback from the hand wielding paint brush or chisel. So here again, as we did when discussing the first characteristic of craft, we have arrived at a rather negative characteristic of art: a work of art can be produced without there being a distinction between means and end although not necessarily so.

There is another way in which the distinction between means and end could be interpreted. We have suggested that art is associated with the expression of an emotional experience, and it is a fact that most artists hope to have an audience or clientele. It could be argued therefore that the work of art itself is a means to the end of conveying an emotional experience to others less gifted who need the work of art to enrich their lives as a cripple needs a crutch. But no artist would say that this is a primary characteristic of art. What motivates the artist is a compulsive need to understand an emotional experience and thereby ease his own mind. He explores his sensuous experience by letting his imagination work upon it, thereby raising the experience to a fully-conscious level. In the course of doing this his skill or craft has enabled him to

produce something which encapsulates his experience – a poem, a painting, a novel, a symphony, and so on. It would therefore be quite wrong to conclude that a work of art is necessarily and simply a means towards the end of arousing a certain emotional state in an observer. If this were so every speech by a political or religious orator, or every advertisement, could be a work of art. If the artist feels the need for an audience it is because he hopes to find in its reaction an assurance that he has hit the emotional nail on the head. He hopes to find that he has been spending his time on a fairly universal experience of life and not some private hallucination.

From this brief discussion of the nature of craft and art one may conclude that art is more than pure technique: more than the conscious working-out of means to achieve a conscious preconceived purpose. Art is essentially an activity in which an artist explores and expresses an emotional experience. But a skill or craft is an important ingredient. Without it the exploration will be ineffective and the expression will be little more than description. To say 'I am happy' is to describe an emotion to classify it and not to express the particular emotion that is felt. An expression of emotion must convey the uniqueness of the experience and enable the artist (and perhaps his audience) to know why he has that feeling in that particular context. Art is evocative: it calls attention to feelings about aspects of life that other people have half felt but have not recognised or brought to a fully conscious level.

To associate art with the expression of emotion is not to suggest that the converse is true, that is, that anything causing an eruption of emotion is necessarily an artistic activity. The foregoing distinction made between expression and description should be sufficient to dispel any such notion. The euphoria that swept over Archimedes when he leaped from his bath shouting 'Eureka' did not make his solution of a problem of physics a work of art. All solvers of tough intellectual problems of whatever kind shout 'Eureka' if only metaphorically.

The history of science and philosophy is the history of man's rational thought. The history of religion is the history of man's efforts to come to terms with the fact that he is conscious both of not knowing why he is here and that reason cannot help him discover why. The history of art is the history of man's feelings about his relationship to his fellows, to nature, and to God. These histories have a centripetal effect: they draw men together by providing contexts in which, and languages by which, man can communicate ideas and feelings. No man is complete if he ignores any one of these three histories. In particular, if man collectively ignores the history of feeling, the emotional springs of life will dry up and he will find that he has inherited T.S. Eliot's *Waste Land*. He will die of boredom after a fruitless search for more and more amusement, which is a not unknown contributory cause of the downfall of civilisations.

We are now in a position to consider what can be meant by the statement that engineering is as much an art as a science. One must conclude that it is true only in the null sense, that is, because engineering is neither. Engineering fits somewhere between art and science in the spectrum of knowledge. We have seen that engineering has links with science through the engineering sciences. Any engineering science has some of the characteristics of science in that it is self-generating, cumulative, never-ending and can command general agreement. But there the similarity ends. The links with art are even more tenuous. Firstly, like art but unlike science, engineering is concerned with creating things rather than theories about things. Secondly, because the engineer rarely has all the necessary data for a complete analysis of his problems, he has to call upon his experience and flair and often take a leap in the dark. Engineering papers purporting to outline the 'current state of the art' are attempts to describe this experience for the benefit of others. One must admit, however, that 'current state of technology' would be a less grandiose phrase.

There is little doubt that engineers, and indeed the public, often have aesthetic feelings about some of their products. The beauty of a Rolls-Royce or Concorde is undeniable, and as moving as a beautiful piece of hand-made furniture or a well-proportioned building. But an elegant solution of an intellectual problem can also give rise to such feelings, whether it be a problem of design in engineering, of devising a crucial experiment in science, or of proving a theorem in mathematics. Aesthetic feelings are not the sole province of art, nor does all art give rise to aesthetic feelings. It seems that it is not possible to centre a philosophy of art upon the concept of beauty. If one cannot use the presence of aesthetic feelings as a distinguishing feature of art, still less can one use the relative importance of creativity. As we shall see in the next section, creativity plays an equally important role in art, engineering and science, although the form it takes in each case will be different.

The creative process

At the most fundamental level it is probably true that there is little difference between the creative process in art, science and engineering. Creativity stems from man's natural urge to explore his environment. And not only man: the exploratory urge is apparent in most animal life soon after birth and it might be said to be one of the important characteristics which distinguish living from non-living matter. Why a person should be creative in one direction rather than another, however, depends on the motivation directing this exploratory urge. We have seen that creativity in art is motivated by a strong desire to explore emotional experience. Creativity in science is undoubtedly motivated by curiosity about the natural world accompanied by feelings of wonder and awe. Engineering creativity, on the other hand, seems to spring from a passionate desire to make novel things or show that something can be done which has hitherto been thought to be impossible. Even this is not solely the province of man. There is the true story of the chimpanzee who failed to draw a banana into his cage because the stick he was using was too short. When furnished with two hollow sticks he solved the problem by fitting them together. The story goes that he was so proud of himself that he spent his time assembling and disassembling the sticks and forgot to eat the banana.

In speaking of motivation in the above terms, we are not suggesting that artists, scientists and engineers do not also have more egoistic motives like pride and greed. But without the more fundamental driving forces being present, it is doubtful if the baser variety would be powerful enough to sustain the necessary effort over a sufficiently long period to bring their ideas to fruition.

A new idea, whether in science or engineering, arises from a juxtaposition of two or more hitherto unrelated ideas at a subconscious level. Such ideas seem to spring to mind after a period of gestation following an even longer period of sustained thought at a fully conscious level. De Bono's concept of 'lateral thinking'[1], and the modern practice of organising group 'brainstorming' sessions, are efforts to shorten the process by consciously looking for unrelated ideas. Since it is the ability to see analogies between different fields that is important, polymaths tend to be more creative than people who have only a narrow range of experience. A brainstorming session with a group of specialists is an attempt to circumvent this problem. Seeing the analogy between a stone skipping over the surface of the sea and a way of delivering a bomb to blow up a dam is only obvious when someone has thought of it. An oft-quoted scientific example is the analogy between the motion of the tides and motion of the moon which enabled Kepler to solve the mystery of the tides.

Really creative ideas in science, leading to new hypotheses which change the outlook in a whole area of science, usually occur to an individual only once in a lifetime. Einstein's theory of relativity and Planck's quantum theory are cases in point. Not only did the theories solve anomalies and throw up new problems, but they changed the whole framework of ideas within which important parts of physics were conducted. Kuhn's[2] 'normal' science is governed by mental habits and a matrix of ideas implanted by education and training. It would seem that only the subconscious is capable of breaking the circuit: of rerouting ideas away from the usual channels in the brain much as they are rerouted in dreams. 'Intuition' and 'inspiration' are the words usually applied to this process. Of course, the result is sense, rather than nonsense, only when the brain has been fed with the relevant facts and has thought hard, long and logically about the problem, This is why brainstorming sessions with groups of specialists are seldom effective except for superficial problems.

In engineering too it is rare for an individual to make more than one substantial contribution of a revolutionary kind. A recent example was the invention of the transistor by Bardeen and Brattain in 1948 when working in the Bell Telephone Laboratories. This led not only to the growth of a new industry – the silicon chip industry – but also to a completely new set of ideas within which electronic engineers had to work. As a consequence many existing industries had to radically revise their technology. Examples of products already affected are radios, TV sets, Hi-Fi equipment, computers, watches and electronic instruments of all kinds. In addition, the growing use of the silicon chip in control systems is beginning to have a substantial effect on almost every industry.

Another example of a different kind was the development of a gas turbine engine for aircraft propulsion. The gas turbine was not invented by Sir Frank Whittle, because a few gas turbines had been built before he arrived on the scene. It is true to say, however, that he was a pioneer of the gas turbine industry. He it was who first realised that the gas turbine was the ideal power plant for aircraft, and that its failure in other applications up to that time was irrelevant. It was his faith and tenacity which gave the U.K. a head start in the gas turbine industry. Nowadays, gas turbines are used very widely, not only for aircraft propulsion, but

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[1]E. De Bono, *Lateral Thinking: A Textbook of Creativity* (Penguin, 1970).
[2]See page 36.

in peak-load electricity generating plant, as pump drives for transcontinental gas and oil pipelines, as power plant for the navies of the world, and to provide the power on off-shore oil rigs. Any student of engineering, interested in discovering just how difficult it was to gain acceptance of an idea from the commercial and civil service establishments of the period, will find profit in reading Whittle's autobiography[3]. If he compares it with the autobiography of Dornberger[4], who fathered the V2 rocket bomb, he will note some interesting parallels in this respect between war-time Britain and Germany.

That it is very difficult indeed for the brain to break out of its straight jacket of 'conventional wisdom' and change the rules of the game in any sphere, is obvious from the rarity with which it happens. Even within the arts – always thought of as essentially creative pursuits – one finds that an individual artist rarely makes more than one significant advance in a lifetime. Some striking emotional experience may cause him to adopt an original technique which starts a new school of painting, sculpture, music or novel writing. With practice he becomes more skilful at applying his technique, and normally his art shows some development, but he seldom makes a second breakthrough into something really new. This development is the artistic equivalent of 'normal' science: it is a process of filling in the potholes in the trail already blazed. And filling in the potholes is all the ordinary practitioner, whether of art, science or engineering, can ever hope to do.

This last statement is not quite correct. The lively ordinary practitioner can hope to do something more. He can keep his eyes open for the next work of genius, try to recognise it when he sees it, and try to distinguish it from the many new ideas that are false trails. This is not easy. The history of science is rife with controversies between proponents of rival theories all of which at the time seemed to account for the facts. To play a part subsequently in interpreting the work of genius, so that it may be assimilated by lesser mortals, is a valuable contribution because the rigidity of our brain circuits is such that it can be a very long time before the view finally accepted filters down to the ordinary practitioner and begins to be widely used.

It is perhaps a blessing that genuine acts of creation are as rare as they are. It is doubtful whether society could stand a greater rate of change of fundamental ideas than exists at present[5]. Looking at the history of science and technology from 10 000 BC to 1850 we have seen that both proceeded by fits and starts. There were long periods of consolidation, and even regression, broken only by short periods of rapid development. But within the last fifty years mankind has been faced with a quite phenomenal rate of change in science and technology which may yet turn out to be excessive. Certainly in the Middle East the rapid westernisation of Muslim states, made possible by oil wealth, has brought about a dangerously strong reaction. Inevitably, with the imported western technology came an alien culture which could not be assimilated at such a rate. But even the western states themselves are creaking under the strain of economic and social problems caused by technological change. The present rate of change is not surprising when one remembers the fact that the vast majority of all the scientists who have ever lived are still alive today, and that science and technology are now very closely linked, each stimulating the other.

Let us now leave the subject of radical innovation and consider the normal process of design in engineering. This is what gives engineering its unique character.

Engineering design

There are two aspects of the process of design in engineering which need distinguishing. The minor one is concerned with making a product more attractive to the customer: *industrial design* is the not-very-informative name given to this activity. Industrial design may be merely a matter of cosmetics to increase the aesthetic appeal of the product. Changes of this kind occur relatively slowly because current fashion and natural conservatism set a limit to the degree of novelty which will be acceptable to prospective customers. On the other hand, industrial design may also include ergonomic considerations. Ergonomics is the study of ways and means of fitting a machine to the human operator. The objective is to reduce human fatigue, increase user-efficiency, and so far as possible make the operation foolproof or at least fail-safe. Many failures put down to 'pilot error' are due to ergonomic shortcomings in the design, which manifest themselves when unusual events put the operator under pressure. It follows that industrial design in the full sense is most important. A successful outcome is likely only if the industrial designer is brought into the design process at an early stage, and if he works closely with the engineering design team.

The major part of the design process is concerned with designing a device – whether it be a machine, instrument, power plant, bridge, dam, or chemical plant – which will do the job expected of it with the

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[3]Sir Frank Whittle, *Jet: the Story of a Pioneer* (Muller, 1953).
[4]Walter Dornberger, *V2* (Hurst & Blackett, 1954).
[5]See Alvin Toffler, *Future Shock* (Pan, 1970).

desired efficiency at a competitive cost. This we will refer to as *engineering design*. It may or may not be associated with *invention*. Just how much novelty is required before the word invention becomes appropriate is difficult to say. The simple answer is that the new device or process is an invention if the idea is patentable. It is engineering design with which we shall be concerned here.

We noted at the end of chapter 3 that progress in engineering is normally by evolution rather than revolution, because of the dire consequences to customer or firm which may result from error. It follows that much engineering design simply consists of using codes of practice and of modifying existing designs by extrapolating a successful design to a larger size. Even then, sometimes the extrapolation is based on poor engineering science foundations and leads to disaster: the failure of the large concrete cooling towers at Ferrybridge power station is a good example. We shall have in mind, however, only cases where a new concept is employed. The new concept may be an original application of an existing device or principle which necessitates a great deal of adaptation, or a new device for serving an existing purpose. An example of the first is the translation of the principles of jet propulsion to a marine environment which led to the hovercraft. An example of the second could be the replacement of a manually-controlled machine tool by a computer-controlled version.

Once the basic idea has been formulated, the design process in engineering becomes one of working out the details to see whether it is practicable. To do this it is necessary to call on all the relevant technologies and engineering sciences. We have seen that the engineering sciences are essentially analytical. They are built up from the solution of small manageable problems each of which can be studied in isolation. The comprehensive empirical theories which result then enable new situations to be analysed. Engineering design is concerned with the synthesis of relevant deductions made from a number of engineering sciences and technologies. For example, the design of a new type of gas turbine will draw upon: engineering thermodynamics (for cycle calculations), fluid mechanics (for blade-shapes and ducts), strength of materials (for stresses in moving parts), mechanics of machines (for shaft whirling speeds, blade vibration, bearing loads), control theory (for control systems) and properties of materials (for choice of suitable materials including lubricants). The one component of the gas turbine where theory is still inadequate is the combustion system. Here the processes of combustion and gas flow are so complex that design rests largely upon the experience of the combustion technologist.

Engineering design is essentially a matter of thinking of a number of alternative solutions to each problem. The designer's skill and experience is most vital at the points where he has to exercise his judgement in choosing the best alternative. He will almost certainly find problems for which there is no solution with current knowledge: for example he may need a material of strength and density which does not yet exist but which the materials technologist thinks is possible of achievement. Research programmes are put in hand and the designer will tentatively assume that solutions to such problems can be found before the design has to be finalised. The design of any large-scale project always proceeds side-by-side with a relevant research programme and this has to be allowed for when predicting completion dates. As each draft design is produced the performance is estimated to see if it meets the specification. Production engineers will be making preliminary designs of any special machines and tools required for the production line, and will be estimating costs. They will be feeding this information back to the design team with suggestions for design changes which will reduce the cost of production. Once the final draft is accepted a prototype will be built and thoroughly tested. Further modifications to the design will usually be called for, and a Mark II prototype may be built.

In speaking of a 'production line' and a 'prototype' it is clear that we have had something like a gas turbine in mind. That is, something of moderate size of which more than one-off will be produced. If, on the other hand, the project is a new kind of suspension bridge, there will be comparable stages in the design process but the words we have used will be inappropriate. For example, for production engineers one would read construction engineers, for special machines and tools one might read special giant cranes or caissons, and for prototypes one would read scale models.

From this brief account it should be clear that a modern chief designer has to sift an immense amount of specialist advice, both technical and economic. In making his decisions he will be seeking the best compromise between the conflicting requirements of high performance and low manufacturing cost. Depending on the nature of the product, 'performance' may be measured in terms of running cost, maintenance cost, operational life, or a combination of these. Moreover he will have to take many more things into account than his predecessors. For example, he has to be aware of the effects his product will have on the environment pollution, health hazards and noise. He will be conscious of safety requirements, and of legislation on product liability (that is, the liability of his firm for compensation in the event of failure of the product). If his design

calls for radical changes in manufacturing methods he may have to take account of the effect on industrial relations within the company. Increasingly he will have to consider the cost of eventual disposal when the product has reached the end of its useful life, and the necessity for making it easy for scarce materials to be recycled. This is all a consequence of a rising standard of living in an increasingly populated world.

In recent years much has been written on design methods in the abstract, to try to systematise the process of design with the aim of increasing the pool of innovative ability. Some writers have been trying to produce an engineering science called 'design science', but so far there is no agreed formulation which could usefully be imparted to students of engineering. It seems that what has been of value in all this effort has been made available through short courses run by people with stimulating personalities. In saying this, we are not suggesting that these valuable attempts to systematise the design process should cease, but merely that so far success has been elusive. Nor are we suggesting that a useful critical attitude to design cannot be implanted in the student by a study of practical examples, and by requiring him to design some piece of equipment which he will help to manufacture and use in the laboratory. Furthermore, there are new design techniques that need to be imparted to the student: in particular those associated with the use of computers. Banks of data can now be made easily available to the modern designer, and the computer enables him rapidly to assess the effect of any changes he makes to the variables at his disposal. He is thus able to consider a vastly greater range of alternatives than his predecessors, and is much more likely to find the optimum solution to his design problem. The engineering student clearly has to be made aware of these techniques, and of the way they can be dovetailed into the production process using numerically controlled (NC) machine tools.

What we are suggesting is that at the end of this teaching process, which lays the foundations, it is still desirable for the aspiring designer to work under a first-class practitioner in the world of engineering outside the controlled conditions of a laboratory or teaching establishment.

This last section should have emphasised the point made earlier, that engineering is essentially *action* – design, construction, development – and action requires a decision to do one thing rather than another. This aspect we shall proceed to consider in the next two chapters. There are broad decisions to be made by a society about what sort of technology it should develop: advanced technology or 'alternative technology', for example. Such questions are closely bound up with what might be called 'engineering ethics', and the important place that ethics will occupy in any philosophy of technology was stressed in chapter 1. The next chapter will deal with these topics. Then there are more detailed decisions to be taken about which specific technological projects to pursue to meet given purposes. In this context, there are associated questions of how the risks involved can be assessed, and how society can control the social consequences of technological decisions. These matters will be discussed in chapter 6.

Chapter 5

Choice of Technological Futures

> Ethical problems arising from technological activity; a code of ethics for engineers?; broad categories of technology (advanced technology, alternative technology, why advanced technology will prevail).

There are two broad classes of decision-making in the technological sphere: (a) broad decisions about the type of technology that a society wishes to use to supply its material needs, and (b) detailed decisions about the choice of a specific technology to meet a given need. The first class, discussed in this chapter, arises directly from the social impact of technology and involves such questions as 'Does advanced technology cause "alienation"?'; 'Would an alternative, appropriate, or intermediate technology serve our needs rather better, and is there any real distinction between these terms?'. The key question here is 'Does a society in practice have much option about the type of technology it can adopt?'.

The second category of decision-making involves such questions as: 'Should a breeder reactor programme be started?', 'Should lead be banned from petrol?'; 'Should we initiate a programme of district heating using combined heat and power plant?'; 'Should a channel tunnel be built?'. It will be necessary to see if any general principles can be enumerated as a basis for taking such decisions. The crucial question in this category becomes: 'Is technology now so sophisticated with such far-reaching consequences that it is almost impossible to make rational choices between technological options?'. Chapter 6 will deal with such questions.

Both categories of decision will be based on more than mere economic considerations and, in particular, ethical considerations will play an important part. Before trying to answer the foregoing questions, therefore, we will discuss the nature of the ethical problems which arise as a result of advances in technology.

Ethical problems arising from technological activity

Fruitful concepts, whether scientific or philosophical, cannot be fully defined in simple terms. Their meaning can be made clear only by exploring the way they are used in the theory in which they arise. The concept of ethics is no exception. One must have a starting point, however, and we shall take it that ethics refers to that aspect of our lives wherein we try to harmonise our desires and actions with those of other members of a community using moral persuasion instead of lies, force or bribery. The community may be of local, national or international dimensions, but we shall use 'society' in what follows and leave the context to indicate the relevant dimension. This incomplete definition implies that an isolated individual on an island could never be faced with an ethical problem. He or she may, of course, have religious problems.

Those who believe that morality springs from religion will have little difficulty in accepting the foregoing partial definition of ethics. Others, however, may say that by referring to 'moral persuasion' in a definition of ethics we are begging the question. We could reply simply that most partial definitions involve a circular argument. A scientific example is provided by: 'energy is the capacity of a body to do work' and 'work is a form of transfer of energy'. But the difficulty can be resolved rather more satisfactorily in the following way.

Humanists and agnostics take a pragmatic view of ethics and believe that the ultimate answer to 'Why should I do this?' is something like 'Because I am a man, and if mankind generally did otherwise no stable society could exist and ultimately there would be no human race'. In other words, they believe that ethical values and concepts — like aesthetic values and concepts — are grounded in the nature of our species. No

transcendental backing is required. On any theory of ethics of this kind, a moral code is a digest of past solutions to ethical problems. It is simply an *aide-mémoire*; although a very important *aide-mémoire* because it embodies a society's collective experience of what has been regarded as correct ethical behaviour in the past. It saves thought in all but the more unusual situations. For example, we do not want to have to rehearse all the arguments as to why stealing is wrong every time we are tempted to keep a borrowed book: we refer to our moral code. On this view our partial definition of ethics involves not so much a circular argument as a spiral argument. The solution of an ethical problem becomes a process of successive approximation using past decisions, like legal precedents, to enable us to home in on a solution. Having said this, it is time to consider how ethical problems arise in a technological context, and then discuss some examples.

We emphasised in the Introduction that technology affects our social structure in two ways: firstly through the means of production we adopt, and-secondly through the devices technology puts into the hands of mankind. One does not have to be a Marxist to believe that the organisation of the means of production has a profound effect on the way in which we live. One has only to look at the historical development of technology in a social context as did Lewis Mumford in his *Technics and Civilisation*, and indeed the contrast between the way of life in mediaeval times and during the industrial revolution is well known. Or one can look at the variations in the world today between countries at differing stages of industrial development. The use of computer-controlled machine tools and robotics in production processes is certainly going to have a profound affect on the social fabric of industrialised countries.

The effect on our life of the products of technology is just as significant. We have, for example, large civil engineering works bringing water and power to arid regions; we have the effect on our lives of vastly increased mobility due to the motor car and aircraft, and of the immediacy of news coverage by television; and now we are faced with major changes due to the deployment of computers and associated information systems.

There is little doubt that technological development has been one of the greatest single engines for change in society. Archaeologists have recognised this by referring to epochs as the bronze age, iron age and so on. No doubt future archaeologists will refer in due course to the fossil-fuel age and the silicon age. Some people might demur and argue that throughout history the struggle for power between tribes and nations has played a larger part: but so often once the armies had done battle the life of the ordinary man went on much as before. Such changes as did occur were largely due to the technological changes stimulated by military requirements, or to new technologies that the conquerors brought with them.

Recently there has been much talk about 'Technological Assessment' (TA), particularly in America; TA is supposed to predict the social consequences of technological developments. 'Think tanks' are all the rage, trying to predict possible futures. One may doubt the value of such exercises. would anyone fifty years ago have predicted that fifty years later man would have walked on the moon watched by a television audience? Would they have predicted the achievement of supersonic flight, nuclear power, the microchip, laser beams, or silica light-fibres for telecommunications? The ingenuity of man is limitless and quite unpredictable. If one cannot predict the technologies, still less can one predict specific social consequences. It would be fool-hardy to suggest that anything is impossible. One might argue that the so-called laws of nature place a restriction on what is possible; and at any particular stage of development so they do. But sometimes such laws are shown to be special cases of more general laws, as when Newtonian mechanics were subsumed under Einstein's mechanics, and this can lead to something becoming possible that was hitherto thought to be impossible, that is, the conversion of matter into energy.

Among the most vocal forecasters of the future are those who advocate self-supporting communes and steady-state economies running on renewable resources. One might call it the 'back-to-nature' syndrome. Surely the incredible inventiveness of man would make nonsense of such a future. The continuous process of solving problems and creating new ones is what being human is all about. The ant can exist in a steady-state society but not a human being. Man is not going to relinquish his hope for a better life because a few comfortably-off conservationists persist in crying wolf. Furthermore, such an approach is quite impractical in a world in which the population is likely to double in the next thirty years, and in which our moral sense has developed to the point where we feel bound to be concerned with feeding, clothing and housing that population.

Suppose we admit that the possibilities will be much greater than can be foreseen and that a full-blooded use of technology is necessary to cope with the population explosion – unless two-thirds of the world's population rush lemming-like into the sea. We might then say: 'Perhaps we *can* do anything, but *ought* we to do particular things A, B and C?'. Once we ask a question involving 'ought' we are involved with ethics.

In this context we are asking whether certain fields of inquiry should or should not be pursued. Of course any individual can legitimately say that he has a conscientious objection to working on a particular project, but it will have little effect on the world because someone else somewhere will certainly do the work. One simply cannot stop the search for knowledge and the inventive process. Once Adam took a bite of the apple from the tree of knowledge there was no turning back. Man's capacity for innovation, and for handing on knowledge from one generation to the next, is one of the important characteristics which distinguishes him from other animals.[1]

But the question was 'ought we' or 'ought humanity', not 'ought I', do something. It is the realm of collective ethics, not personal ethics, that is relevant here. By collective ethics is meant the moral stance adopted by a society. Certainly a *particular* society can stop the application of a *particular* piece of knowledge. But woe betide it if this leads to other societies gaining the edge in this competitive world. It will be disastrous for any developed country to opt out of the microelectronic revolution because it thinks it morally wrong to deprive people of the job they were originally trained to do.

This does not mean that societies have no real choices to make. The exponential expansion of science and technology in the last two hundred years has given man a bewildering range of alternative courses to pursue, and we can and must decide which horses our own society should back with public funds. At present in the U.K., the government makes its choice with advice from Standing Commissions, Royal Commissions, Parliamentary Committees, Research Councils, and Committees of Inquiry[2]. The development of appropriate machinery, for making rational decisions about large-scale technological projects with very long lead times, is still in its infancy, and the next chapter will have something to say about this topic. While economic factors are often paramount, there are other factors having an ethical content which do play a part in the decisions. What are some of the collective ethical problems that face a society?

One is how far a society should take account of the needs of future generations. Should a society husband scarce mineral and fuel resources now to leave more for the future? Governments and businesses have to compare present costs and benefits with more distant ones when planning expenditure. For example, is it financially worth spending a great deal now on developing combined heat and power plant (CHP) for district heating schemes to obtain future savings on fuel costs? Using our power stations in the back-pressure or pass-out mode to enable their waste heat to heat our cities would undoubtedly save a considerable amount of fossil fuel for future generations. Calculations show that if one-half of the U.K.'s electricity was produced by such plant, the national primary fuel consumption would be reduced by about 8 per cent.

When estimating whether such schemes are economically viable, in comparison with the present mix of individual heating appliances, one has not only to make an assumption about the rate at which fuel prices will rise, but decide on the rate of interest to employ when *discounting* the running costs. (£100 now is worth £200 in 10 years' time at an interest rate of 7 per cent; conversely £200 in 10 years' time is worth £100 now at a *discount rate* of 7 per cent. The total cost of a project of capital cost C and annual running costs R1, R2, etc., is found by discounting R1, R2, etc. to the starting year over the life of the plant, and adding the sum of these to the capital cost C. This yields what is called the 'present value' of the total costs.) One reason for discounting is that with continued economic growth it is reasonable to expect future generations to be better off than the present one. In 1969 the Treasury laid down a Test Discount Rate (TDR) of 10 per cent to be used by public enterprises when making investment decisions. In 1978 this was reduced to 5 per cent for the nationalised industries. A high discount rate means that savings arising in the future are worth very little now and, with a TDR of 10 per cent, energy conservation schemes involving CHP often seem uneconomic. The lower the TDR the more future savings are worth, and the more our economic decisions are biased in favour of future generations. The choice of TDR is thus a collective ethical decision.

The question arises as to how far ahead it is reasonable to look. Certainly to our children's lifetime: we cannot help but be concerned for their welfare, however unwelcome the concern may sometimes be to the recipients. But it can be argued that we cannot anticipate, still less solve, the problems of our grandchildren.

A second but related problem of collective ethics is the amount of choice a society should allow its individual consumers. It is related to the first because too much choice now can mean less for future generations. To take the example of district heating a stage further: where a CHP scheme is adopted the individual consumer will have no choice of heating system or fuel. By saving fossil fuel now, however, future generations would have more freedom of manoeuvre and more time in which to develop alternative sources

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[1]This is not to be taken as implying that no other animals do this. Nor when making remarks like 'man is a tool-using animal' is it implied that no other animals use tools. All that is meant is that these characteristics are much more marked in *homo sapiens* than in any other species. That most, if not all, human characteristics are to be found in embryonic form in some other animals should surprise no one but a religious fundamentalist.

[2]See for example: *The Windscale Inquiry: Report by the Hon. Mr. Justice Parker* (H.M.S.O., 1978).

of energy such as fusion. To take another example, is it really sensible to burn oil in order to ship cars across half the world from one car-producing country to another? Surely this is a particularly senseless form of international trade, except in terms of giving consumers more choice. Consumer choice is apparently always regarded as a benefit. To gain public acceptance of restrictions on choice a government has to muster all its arts of persuasion. Can the demand for unrestricted choice really be justified?

Another problem of collective ethics is how to arrive at a reasonable attitude to health and safety. How much of our valuable resources should we devote to this aspect of our lives? At present we seem bent on making every industrial activity a thousand times safer than widely accepted risks in the home and on the roads. Would it be more sensible to be a little less profligate with expenditure on safety measures and more liberal with compensation to those unfortunate enough to sustain the accidents? Would the U.K. – a very small island – have achieved what it did if our forefathers had had the present attitude to risk? How far is our present attitude inhibiting entrepreneurial activity and hence exacerbating the unemployment problem? But, on the other hand, how far is it justifiable to sacrifice individuals at random for the sake of entrepreneurial activity whose ultimate benefits cannot be predicted?

A fourth problem, but again related to the attitude adopted to our own lives, arises because of developments in medical technology and bio-engineering. These developments are keeping us alive much longer, so the question arises: under what circumstances should the medical profession cease to prolong life or even assist death? This is going to be a major ethical problem in the next twenty years if the average age of the population continues to increase. A no less pressing problem in this area is the high cost of sophisticated medical equipment (X-ray scanners, automated laboratory analysers, kidney machines, etc.) and of organ transplants. This leaves fewer resources for the less exciting sphere of preventive medicine which could help a far larger proportion of the population.

A fifth problem of collective ethics is what stance should the developed countries take to the developing countries. Is there any hope of a peaceful and constructive world if the 'haves' do not help the 'have nots'? Is there any hope of stabilising the world population if the standard of living is not raised significantly in the Third World? Many people think that acceptance of birth control depends on high living standards. Should not the advanced societies accept the risks of nuclear power so that fossil fuel is available for the less advanced? How do we balance the clash of interest between wishing to be independent of difficult overseas suppliers (say by restricting imports from politically unstable regions) and wishing to help these regions? We cannot help them if we refuse to take their products. It is not very edifying to watch the governments of the developed nations wriggling on the hook cast by the Brandt Commission Report, which was an attempt to see how the Western world could help the developing nations without beggaring itself in the process.

Finally, a sixth problem is concerned with man's attitude to his environment. We have said that the mainspring of technology was the recognition that we were not completely at the mercy of capricious gods and that we could modify and adapt the world to suit our purposes. The view that man was the supreme species and had a right to lord it over the rest of the living world has had a long history well supported by Christianity through the Book of Genesis. It certainly goes back to Aristotle who said that plants were created for the sake of animals and animals for the sake of men. In recent years this view has been changing as we have become more conscious of the combined effect of population growth and widespread use of technological processes upon the environment. It would go too far to say that man is now seen more as a partner in the living world than as an overlord, but at least it is recognised that if he is to maintain his mastery he has to co-operate with his environment rather than merely exploit it. The post-war spate of legislation to limit pollution, to restrict the defacement of landscape by reservoirs and motorways, and to preserve wildlife, is sufficient indication of the trend.

Man is certainly acquiring a conscience about his effect on the bio-sphere, and so environmental problems have ethical overtones. The matter is not unrelated to the problem of what his attitude should be to future generations. One of the most moving statements of what this new approach to the environment should be is found in Chief Seattle's response in 1854 when the Great White Chief in Washington offered to buy a large area of Indian land: a few extracts should suffice.

'What is man without the beasts? If all the beasts were gone, man would die from a great loneliness of the spirit. For whatever happens to the beasts soon happens to man. All things are connected. So that they will respect the land, tell your children that the earth is rich with the lives of our kin. Teach your children what we have taught our children, that the earth is our mother. This we know: the earth does not belong to man; man belongs to the earth. Whatever befalls the earth befalls the sons of the earth. Man did not weave the web of life; he is merely a strand in it. Whatever he does to the web he does to himself.'

These are six examples of what can be called collective ethical problems – they involve the attitude which

a technologically advanced society takes either to future generations, to life in its own society, to the Third World, or to the environment. There are no easy answers to any such problems, nor can there be any final solutions – they are not that sort of problem. They are perennial questions to which each generation in turn must give some sort of answer. This is as it should be: again, it is what being human is all about. The answers will change with the moral development of mankind and the technological means at its disposal. And let no one suggest that there have been no changes for the better in man's moral stature. Although there are still great evils – and evil men – the generality of the population no longer delights in the burning of witches, laughs at cripples, or knits at executions. And at no other time in history has there been such an abundance of national and international welfare systems trying to help the less fortunate among us. Of course it is impossible to prove that there has been a *net* improvement in moral stature, because it is impossible to quantify past and present evils. It may well be that evils in the concentration camps of Stalin and Hitler were unmatched by anything achieved by Ghenghis Khan.

Why do the perennial collective ethical problems seem so prominent today? It is because of the power afforded by modern science and technology. What was accepted as inescapable circumstance or fate is becoming increasingly within our power to regulate. If industrial society has created these problems, or sharpened old problems, should we put the clock back to avoid them? Should we opt out and succumb to the 'back-to-nature' lobby? Surely this would be throwing the baby out with the bathwater. With all its faults, in many respects the industrial age has been the most successful mankind has known. A larger fraction of society eats better, is better informed, lives longer and more comfortably, has safer and more satisfying work, and is more mobile, than in any other age. It is part of the conventional unwisdom to deny this, and to look back at some other period in history through rose-tinted spectacles, but one would have little success in convincing the developing countries that it was anything but true.

Certainly the industrial age has many imperfections, and a clear indication is provided by the statistics of crime, stress diseases, and the vast consumption of tranquillisers and anti-depressants. Obviously we hope to move forward to a better future: where mankind's material needs are easily satisfied and where we can concentrate on satisfying man's psychological needs. We all know broadly what these are. Firstly, there is the need for emotional attachments to people, places, local organisations and ways of behaving. Such attachments provide a feeling of security, identity and status on the one hand and an opportunity for service on the other. These are all fundamental human needs. Secondly, society must be so organised that a man can act in accordance with his conscience and with freedom to follow his religious inclinations: a society which is not might be called a psychic polluter. Thirdly, there is a need for stimulus and challenge. Man's passion for competitive and dangerous sports, and difficult pastimes such as trying to master a musical instrument, are sufficient indications of this basic need.

It has been suggested that we are slowly beginning to move in the right direction, towards what some call the post-industrial society. There has been increasing talk about the importance of job satisfaction, diseconomies of scale ('the small is beautiful'), and devolution of responsibility from central to local government; and there is widespread acceptance of pollution controls, product regulations and other measures concerned with the quality of life rather than with economic growth. No one pretends that the transition to the post-industrial society will be painless. The changes in our attitude to work and leisure that will be required in the next ten years under the impact of microelectronics and robotics will be particularly traumatic. But we can move forward only by building upon what we have. We can solve our problems only by the application of yet more reason and intelligence, albeit with more awareness of man's psychological and emotional needs than hitherto.

Unfortunately there are signs of a swing to irrationalism, epitomised by the pseudo-religious groups that abound in the U.S.A. This regression has been encouraged by the writings of those who suggest we are spiritually and emotionally crippled by our commitment to scientific ways of thinking. No doubt the warning is justified and timely, but we need not be crippled in this way if we remember that science can never answer the ultimate questions that a self-conscious being like man is bound to ask, about who he is, why he is here, and what his role in the universe can be. It is just because he *can* ask these questions, which other animals cannot, that he *has* ethical problems and that ethical statements are significant, meaningful, propositions and not just expressions of transient emotion or feeling.

A code of ethics for engineers?

Before leaving the subject of ethics, it may be worth a digression to examine the practicality of a proposal that engineers should adopt an explicit code of ethics for their profession as do physicians. At the Second General Assembly of the World Medical Association in Geneva in 1948, the Physicians' Oath was discussed and the resulting 'Declaration of Geneva' included such promises as:

'Now being admitted to the profession of medicine, I solemnly pledge to consecrate my life to the service of humanity.'

'The health and life of my patient will be my first consideration.'

'I will hold in confidence all that my patient confides in me.'

'I will not permit considerations of race, religion, nationality, party politics or social standing to intervene between my duty and my patient.'

These extracts will be sufficient for our present purpose.

In 1970 Professor Thring wrote an article for the September issue of the Chartered Mechanical Engineer entitled 'Our Responsibility for Mankind' and suggested the following 'Hippocratic Oath for Engineers'.

'I vow to strive to apply my professional skills only to projects which, after conscientious examination, I believe to contribute to the goal of co-existence of all human beings in peace, human dignity and self-fulfilment.

I believe that this goal requires the provision of an adequate supply of the necessities of life (good food, air, water, clothing and housing, access to natural and man-made beauty), education and opportunities to enable each person to work out for himself his life objectives and to develop creativeness and skill in the use of the hands as well as the head.

I vow to struggle through my work to minimise danger, noise, strain or invasion of privacy of the individual: pollution of earth, air or water, destruction of natural beauty, mineral resources and wildlife.'

The first point to note is that although both statements imply a dedication to the service of humanity, the physician's oath goes on to deal specifically with the relationship between the doctor and his patient. The physician pledges that the well-being of the patient will be his first consideration, regardless of any religious or political beliefs he may have. In conjunction with the promise to hold in confidence all that the patient confides in him, this must imply that the health and life of his patient is to come first, whatever feeling he may have as to whether the continued existence of his patient may be beneficial or harmful to humanity. Herein lies the difficulty. Some doctors no doubt take this literally, but others will temper it after examining their conscience. What should a doctor do when he finds that his patient is a homicidal maniac; that he is a terrorist injured in his own bomb explosion; that he has been injured in a motor accident and has an alcohol level way beyond the legal limit? All these patients are potential murderers. The rational man would surely expect the doctor to remember the overriding pledge at the beginning of his oath where he consecrates his life to the service of humanity. How is he serving humanity by knowingly releasing potential murderers on an unsuspecting public? Should he not, therefore, override his promise of confidentiality and report the situation to the appropriate authorities? We may note then, that even with an oath of this very restricted form – dealing with the relationship between one individual and another – there are very considerable difficulties. So much so that no doctor could be struck off the register merely for failing to observe a portion of the code.

If a code dealing with a simple one-to-one relationship is difficult to apply, how much more so is the code proposed for engineers. The engineer has responsibilities to his employer, his profession and to the public, and he has potentially a much wider sphere of influence than the physician. It is difficult to find anything at all in Professor Thring's proposed code that applies specifically to engineering. Read out of the context of his article, the code can be seen to apply equally well to any professional group whether it be of politicians, social workers, teachers, artists, novelists, playwrights and so on. Any conscientious person whose activity has any influence on the world around himself would be happy to take such an oath.

The next point to note is that a code covering all the desirable effects of any activity does little more than outline what are currently regarded as the characteristics of a good society. In any practical situation, however, one is usually choosing to have more of one characteristic at the expense of another, and one has to decide which of various means is most likely to achieve the end. In other words we have the normal state of affairs – human beings faced with difficult ethical decisions – and the code is of very little assistance. In the unreal world of party politics we are led to believe that the decisions taken by members of the other party are evil decisions taken by immoral persons: in the real world, of course, we simply have human beings who genuinely believe that their policies would be more effective than those of their opponents in achieving the good society outlined in the code. One group will believe that peace would be more likely to be achieved if

the nation disarmed, and another that adequate military preparation is required. The code provides no help to an engineer deciding whether to work in a military research establishment.

An ethical code is of help only if it saves us thought, and it can do so only if it deals with relatively simple situations. There are few situations where stealing might be justifiable, so the injunction 'Thou shalt not steal' is a useful guide-line. There are, of course, situations where observance of even this seemingly obvious rule might not lead to a right action. For example, a man with a starving family in a society with no welfare organisations and no access to a plot of land, would receive little blame for stealing food for his family, and indeed it could be argued that he has a duty to do so. There are no absolutes in the ethical sphere, and we are much more often faced with a choice between various goods or various evils than a straight choice between a good and an evil.

From the foregoing discussion, the reader will not be surprised to learn that Professor Thring's suggestion has received little support from the professional engineering Institutions. But if such a code would be of no direct help to engineers, might it not help them indirectly by showing the public that as a body they espouse ideals which should be those of every thoughtful citizen?

Broad categories of technology

(i) Advanced Technology

Chapter 2 described the transition from societies based on craft and technics to industrial societies based on full-bodied technology. In the previous section we suggested that we might be passing through another technological revolution carrying us towards the post-industrial society. Gendron[3] summarises the historical process as in figure 5.1. What he calls 'post-industrial technology' is epitomised by a substantial increase in productivity per man; a transfer of manpower from the product industries to the service industries (health, education, etc.); human knowledge and expertise becomes the primary factor of production rather than capital; the primary unit of production becomes the multinational organisation rather than the individual firm; workers become machine minders rather than machine operators; and power technology gives way to information technology in order of importance.

We have argued that the extreme anti-technology movement, referred to as the back-to-nature cult, is unrealistic. Gendron calls supporters of the movement the 'dystopians'. An examination of their reasons for opposing technological civilisation might help us to avoid the opposite extreme the utopian view. Briefly, the dystopians think that the social costs of advanced technology outweigh the benefits: that advanced technology undermines freedom and democracy by stimulating bureaucracy and by promoting the rise of techniques of mass manipulation; that it dehumanises us and is the chief cause of the alienation of the individual both from his fellows and from nature; and finally that it increases the twin dangers of annihilating war and ecological catastrophe.

The utopians, on the other hand, think that the good outweighs the bad; that advanced technology will eliminate scarcity and the aggression of which scarcity is a cause; that it will eliminate famine and disease; that the control of industry by technocrats rather than by capitalists and politicians will lead to efficiency becoming the paramount consideration instead of profit or ideological rectitude, and that this in turn will lead to the proper management of natural resources and adequate control of pollution.

We have expressed the belief that on balance the good has outweighed the bad, and to that extent have adopted the stance of the utopians. But only to that extent. There are no grounds for believing that man's aggressive instincts will be in any way diminished, even if the superhuman task of eliminating scarcity for the world's billions of population were to be accomplished. There will always be wealthy groups or nations facing less wealthy groups or nations; the better educated facing the less well educated; and those in satisfying employment facing the unskilled or unemployed. It is unreasonable to assume that man's competitiveness will ever be limited to the sportsfield. All that we can hope is that man will eventually develop and accept rules for the maintenance of fair competition in the industrial and commercial spheres just as he has done in the world of sport.

We said: 'even if the task of eliminating scarcity was accomplished'. The notion itself is nonsense, however, because technology continuously creates new needs – as fast as one is satisfied another is created. This is an inevitable consequence of man's inventiveness. Post-industrial technology may well be more

[3]B. Gendron, *Technology and the Human Condition* (St. Martin's Press, 1977).

Aspect of Technology Affected	Agrarian	Industrial	Postindustrial
Level of productivity	Supports less than $300 in per capita income	Supports up to $4000 in per capita income; grows at approximately 2 per cent yearly	Supports up to $17 000 in per capita income; grows at 3-4 per cent yearly
Primary product	Food	Manufactured goods	Services
Primary factor of production	Land	Capital	Human expertise
Organization of production	Household	Factory	Integrated nationwide and worldwide economic planning; development of organizational and behavioral technologies
Role of the worker	Crafts Production; worker as skilled artisan	Mechanized Production; worker as machine operator	Automated production; worker as machine monitor
Instruments and machinery	Tool-oriented technology; instrument as extensions of, or replacements for, human limbs	Power technology; machines as replacements for human or animal muscle power	Informational technology; machines as replacements for human brains or sensory receptors

Figure 5.1: Agrarian, industrial and postindustrial technologies (from Gendron, B., Technology and the Human Condition; by kind permission of St. Martin's Press)

successful than industrial technology at meeting the minimal requirements for food, clothing and shelter – what may be termed man's biological needs – but that will not eliminate scarcity which is essentially a relative term. A man will feel poor if he cannot afford a reasonable proportion of the mass of goods and services on which the advertising fraternity spend vast sums in persuading him to want. Figure 5.2 shows how 'needs' have grown in the past seventy years in the industrialised countries, and nowadays there is very little that the majority will accept as being a reasonable prerogative of the few. But even if advertising were drastically curtailed and designed to inform rather than persuade, and even if the wealthy refrained from conspicuous consumption, some forms of scarcity would still exist. We have suggested that real improvement in the quality of life will come only when we seriously consider ways and means of meeting man's psychological needs. To meet such needs, space, clean air, clean water and recreational facilities of all kinds, although not sufficient by themselves, are necessary prerequisites. Such commodities cannot easily be expanded to meet the needs of the whole population and certainly not if the world population continues to increase. This point has been discussed at length in *Social Limits to Growth* by F. Hirsch (Routledge and Kegan Paul, 1977). There will certainly always be competition for resources of this kind.

Finally, technological changes always throw up new social problems and there can be no question of ever eliminating these. The necessity for our children to make difficult ethical choices in their turn can never be avoided. Indeed to remove this necessity would be to destroy their humanity.

Utopia then is a chimera, and mankind would probably die of boredom if it were ever achieved. If one is to take an optimistic view at all, it is that mankind's story will continue on some kind of erratic upward path in spite of many set-backs caused by natural disasters, climatic changes, epidemics, moral back-sliding, or political chicanery. We have said that our only hope lies in increasing our genuine empirical knowledge of causes of events – whether they be technological or social events. Is there something in the utopian view that the passing of the control of affairs from capitalists and politicians to a technocracy is a hopeful sign? Gendron argues that it is, in the sense that the technocrat, proud of his expertise, will do all he can to

extend it. He will tend to favour ploughing profits back into research departments, hoping to increase the stock of knowledge; he will be responsive to criticisms about pollution and other anti-social aspects of his industrial activity because he will see them as indicators of inefficiency; he will favour the increased use of mathematical techniques and information technology for making technological and managerial decisions. In other words, his prime motivation will be the pursuit of effectiveness, rather than profit for its own sake. It is a hopeful sign too that economic planning by governments and by the great corporations is now beyond the capacity of any individual. Increasingly, major decisions must be taken as a result of rational discussion between experts of all kinds – technical, managerial, financial, governmental, and so on. The absolute power that can corrupt individuals absolutely is shared in committee.

Of course the dystopians are undoubtedly right to fear an increase in bureaucracy, and to predict a strengthening of the feeling of the ordinary man that his life is increasingly beyond his control. It has probably always been beyond his control, but at least in earlier times he felt he understood the forces which affected him – the greed of the landowner and capitalist, the personal aggrandisement of kings, the seeking of power by demagogues. He cannot understand the complex processes and expert knowledge required for technological decision-making. If he is not to be totally alienated, then side-by-side with the growth of planning on a world scale must go a decentralisation of the bodies which execute the plans at a local level. For example, the fishermen know that a free-for-all leads eventually to depleted fishing grounds, and that somehow international rules must be formulated and adhered to: government ministers trying to reach agreement might be helped by conferences of fishermen drawn from the nations concerned. The people most affected have to be drawn into the decision-making if alienation is to be avoided. And if it is not avoided, the postindustrial revolution will have, as an equivalent of the Luddite movement in the industrial revolution, a 'revolt of the masses' against the intelligentsia (to borrow the title of a polemic by Ortega y Gasset).

'Alienation' is one of those in-words which can mean all things to all men. We are assuming that what is meant by alienating work is not that it is hard, dangerous, dirty, noisy and sometimes boring, but that it has a majority of the following characteristics. It is work over which the individual has no control as to quantity, quality or direction; which is meaningless because serving no obvious need; which fails to present a challenge or any satisfaction other than the pay packet; and which involves social isolation. There is nothing inherent in advanced technology which means that alienation in this sense must become more widespread. Indeed such technology gives us a greater freedom to choose ways of organising and distributing work in such a way that man's psychological needs are met more adequately, once we have accepted the importance of doing so. Likewise there is no reason to suggest, as do the dystopians, that advanced technology will lead inevitably to increased pollution and faster depletion of nonrenewable resources. Indeed, in the face of demands from an increasing world population, advanced technology is our only hope of reducing pollution and finding ways of doing what we want to do with less expenditure of scarce resources: microelectronics absorb very little electrical power, silica optical fibres can replace copper wire for communication systems, and nuclear power reduces pollution.

The dystopians are not confined to those at the extreme 'back-to-nature' end of the spectrum. Some occupy a middle ground, not denying the value of technology in its proper place, but believing that an 'alternative', 'appropriate' or 'intermediate' technology might serve much of mankind's needs rather better than a complete reliance upon advanced technology. What is meant by these terms and is there any real distinction between them?

(ii) Alternative technology

The terms 'intermediate', 'appropriate' and 'alternative' technology began to be used in the late 1960s, and were originally coined to refer to technologies suitable for the developing countries. To be classed as 'intermediate', a technology is supposed to have the following characteristics: (a) be easily understood so that a technically literate population is not required, (b) be labour intensive rather than capital intensive, and (c) use small-scale plant serving local needs to avoid the need for an expensive transport system. An international conference was called to discuss such matters, under the auspices of the Intermediate Technology Development Group founded by E.F. Schumacher who wrote *Small is Beautiful* (London, 1973). A view was expressed that the term 'intermediate' had overtones of 'second best' and 'temporary', and that 'appropriate' might be a more suitable description.

Soon the environmental and ecological protest groups in the industrialised countries began to see that they had something in common with the intermediate technology groups, and began to argue that the

adoption of such technologies would benefit the developed world also. They argued that an easily understood technology would reduce alienation problems and serve man's psychological needs rather better, and that local small-scale plant would save energy which might become scarce in the very near future. It was in this context that the term 'alternative' came into use, soon to be followed by a multitude of other adjectives such as 'soft', 'non-violent' and 'convivial'. We may conclude, therefore, that the different terms refer to the different contexts in which the simplified technologies are recommended for use, rather than to any difference in type of technology. Most writers on the subject avoid the difficulty of nomenclature by simply referring to the abbreviation AT, and we shall follow suit.

There are two questions then: 'Is AT more appropriate for the developing countries than advanced technology?' and 'Is it a real alternative for the industrialised nations?'. A review of the fate of AT in the Third World by Rybczynski[4] rather suggests that AT has many limitations in the first context. As an opportunity for additional exports from the developed countries it has had its successes, but as a way of helping the Third World, by raising the living standards of the desperately poor, AT has been disappointing. The beneficiaries turn out to be the middle classes and richer farmers rather than the urban and rural poor. Rybczynski quotes as one example the many bio-gas digesters in India and South Korea that never work or work only for part of the year when the ambient temperature is suitable. In cases where the conditions are favourable, and the supply of farm refuse is of constant quantity and quality, one finds them used successfully by a few wealthy farmers. The immediate result is that cow-dung is no longer freely available to the poor who use it as cooking fuel.

Then again, often the products of AT are not of acceptable quality and the population prefers to pay more for the standardised product from large factories. Here Rybczynski refers to the village soap industries started in India, and the unsuccessful hammer mills in Kenya which failed to produce the required quality of maize flour. The more expensive rolling mills proved to be more economic in the long run. The fact is that, even in the developing countries, capital-intensive technologies have a lower marginal cost and are more readily adjusted to meet changes in demand, and managers find it easier to manage machines than people. Clearly AT is no panacea, and there is a growing pessimism about its potentialities among all but the ideologically committed.

While China followed Mao, the proponents of AT always had an example which they could feel exhibited the virtues of AT. The position is rather different now that China has reversed the Cultural Revolution and is sending its technical personnel all over the world to update their knowledge of advanced technology. In fact, as his slogan 'walking on two legs' implied, Mao never denied the necessity for investment in large-scale industrial plant. The small-scale village industries were very largely limited to the production of cement, fertilisers, agricultural implements and building materials.

There is no doubt that many developing countries do feel that AT is second best, and that it is being promoted by the industrialised nations to safeguard their own more advanced industries at home. Furthermore, one cannot help such countries by educating their students in scientific and technological departments of Western universities and not expect them to wish to use that knowledge when they return to their own land and reach positions of responsibility. They will have acquired a taste for advanced technology, which cannot be assuaged by designing cheap solar stills or windmill-driven pumps for villagers. Nor can this kind of thing meet the needs of their vast and expanding urban populations.

(iii) Why advanced technology will prevail

So much for our question as to the suitability of 'alternative technology' for the developing countries. The second of our questions was 'Is AT a real alternative for the industrialised nations?'. We shall argue that the answer must be 'No'. Perhaps the strongest reason why we must pursue advanced technology is the pressure on material and energy resources which will become acute early in the next century. The grounds for saying this can be summarised as follows.

(i) Two-thirds of the world will not be content much longer with a sub-standard of living which corresponds to an energy consumption of about 0.5 kW per man. This must be compared with an energy usage of about 5 kW per man required to give European man the standard of living to which he has become accustomed. Whether we are thinking of water supplies and sewage systems, food, or consumer goods, a rise in standard of living implies the use of more materials – and the production of most materials is an energy-intensive process. Furthermore, although the energy coefficient of an economy (that is, the ratio of the percentage increase in energy consumption to the percentage increase in gross domestic product, GDP) is about 0.7

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[4]W. Rybczynski, *Paper Heroes – a Review of Appropriate Technology* (Prisin, 1980).

to 0.8 for the industrialised countries, it is about 1.2 for the developing countries. Thus a proportionately larger increase in energy consumption is required to raise living standards in the Third World. This is not surprising, because the basic necessities which would be involved in the increase of GDP of the latter are more energy intensive than the frills which form an increase in the GDP of the former.

(b) A doubling of the world population is probable even if current efforts to limit it prevent any increase beyond that. Such a population can be fed only by using modern methods of agriculture which are energy-intensive in terms of fertilisers, tractors, and so on. Also, to avoid soil erosion it will be necessary to restrict the present indiscriminate cutting of forests for fuel.

(c) The working of difficult sources of fuel and minerals (for example, North Sea oil, oil shale, weaker ores) will require more primary energy.

(d) The production of alternative materials, and recycling of scarce materials, will often require the expenditure of additional energy.

(e) When oil becomes scarce the production of liquid fuels for road, sea and air transport will use more primary energy. For example, the production of oil from coal involves the loss of about 40 per cent of the heating value of the coal. Rail transport will no doubt be catered for by increased electrification of the railways, assuming that nuclear power is available.

(f) As the population and standard of living increase, more stringent anti-pollution measures will be necessary and these cost energy.

These energy requirements will be met partly by new power plant and partly by energy conservation measures. Both approaches will require the use of advanced technology. In the case of the former, we shall almost certainly not meet the world's needs without using the concentrated power locked up in the atom – whether by nuclear fission or ultimately by nuclear fusion. It is true that coal reserves are much larger than oil reserves, but when oil becomes scarce the power-producing industries will have to compete with the chemical industries for the use of coal. Chemical industries require hydrocarbons as a feedstock. The anti-nuclear movement seems to think that wind and wave machines will come to our aid if only we pour enough money into their development. Unfortunately, such machines have to be designed to cope with exceptional weather conditions, and so most of the time are operating in a very lowly stressed condition. This implies that vastly more material is required for their construction than for conventional power stations, and we have noted that the materials industries are energy-intensive. The maintenance costs too would be very large – both in financial terms and energy terms.

To conserve energy, we shall need to use such aids as combined heat and power plant, heat pumps, and solar energy systems for heating our homes. Solar heating is likely to be economic only when a sophisticated technology is found for producing cheap electric solar cells in vast quantities. The installation and maintenance costs of the present liquid solar-absorber systems make it highly unlikely that they will be widely used except in regions particularly favoured by the sun. We shall also need advanced technology to reduce the energy consumption of our transport systems, and of our most energy-intensive industries.

There is another basic reason why few industrialised nations can forgo the use of advanced technology. Most are not self-sufficient, but depend upon trade to pay for food and raw materials. Such nations are therefore forced to adopt the most competitive technology. Once the developing countries acquire the means of producing traditional goods – steel, textiles and so on – they can always undercut the older industrialised countries because of their lower labour costs. The only way that the developed countries can compete and pay for essential imports is by selling goods produced by new technologies.

In saying that regard must be paid to the economic imperatives of international competition, we are not intending to imply that no choice whatever is open to an industrialised country. We have said, for example, that no such country can afford to opt out of the microelectronic and robotic revolution. This is surely true – but the direction in which this revolution proceeds is still within our control. The argument that if we do not use technology in such and such a way we shall be uncompetitive, must not be pushed to extremes. Analogous arguments were undoubtedly put forward by the plantation owners when faced with the abolition of slavery, and by the mine owners and mill owners when threatened with the prohibition of child labour. Although in the short-term a unilateral action may have unfortunate economic consequences, if the change is clearly beneficial on social grounds then competitors will be forced to follow suit.

There are essentially two ways in which the microelectronic/robotic revolution might develop – one is life-denying and the other life-enhancing. We can drift into treating it simply as an extension of the industrial revolution, which had the effect of breaking down many tasks into semi-skilled or unskilled operations and thereby denying many people the satisfaction of developing and exercising a skill. The new technology could carry this trend still further, spreading the de-skilling process into white-collar work and even into

professional spheres. The few additional skilled occupations created – principally in computer programming and the design and maintenance of associated equipment – will certainly not compensate for this. Even assuming that society will eventually adopt work-sharing schemes that will eliminate unemployment, to proceed along these lines would lead to a society polarised into a small group of people working hard at challenging problems and a large group engaged on work requiring no initiative or skill whatever. This is the very antithesis of a society designed to meet man's psychological and emotional needs. That such a path would in the end be self-defeating, and lead to stagnation, is the main reason for believing that it will be avoided. The Council for Science and Society (CSS) publication 'New Technology – Society, Employment and Skill', contains the following example illustrating the point.

Consider the case of a computer programmed for carrying out the diagnostic work of a doctor. This is certainly not beyond the bounds of possibility. The doctor works (a) by explicit scientific rules that his training and experience have led him to accept, and (b) by an intuitive knowledge acquired from the practice of his diagnostic skill which he would find it difficult or impossible to describe in explicit terms. An external observer might, after careful study, be able to deduce what much of this intuitive component consists of, and thus program a computer to take both the explicit and implicit rules of diagnosis into account. Indeed, if the program was devised from a study of the work of a number of doctors, the computer might perform rather better than all but the best. Imagine now that a hard-pressed Health Service decides to invest heavily in computer diagnostics, and to staff regional diagnostic units with narrowly, relatively cheaply, trained medical technicians at the expense of broadly educated doctors. It is conceivable that initially the public might be better served by the new system. Eventually, however, the source of skill upon which the programmers can draw will dry up, and medical practice will ossify.

The same bleak picture can be drawn for many possible uses of robots. Robots are often programmed by a skilled craftsman going through the motions required, which are then recorded and repetitively performed thereafter by the robot. How is the craftsman to maintain his skill under these conditions?

So much for the life-denying way of using microelectronics. But the CSS report goes on to explain why this is not inevitable. Suppose the doctor co-operates with a programmer to develop a personal diagnostic computer for his own use, and that he treats it as an aid to 'increase his productivity'. It may also prevent him from overlooking some important question towards the end of a tiring day. He will not always agree with the computer, because sometimes he will spot an unusual set of a patient's circumstances not allowed for in the program. Part of his skill will come to reside in judging when, and when not, to trust the computer. Such a doctor is in a good position to update his programs as medical science advances and his experience is deepened. There is then no danger of ossification. Fortunately, there is a reasonable expectation that such life-enhancing uses of the computer will prevail, because the economics of microcomputers are such that there is no financial advantage in using a large regional computer as opposed to a multitude of small personal computers.

Competition between firms and between nations is inevitable and even desirable. In the long run the prize will go to the firm or country which finds the best way of using its human potential. The microelectronic revolution provides an opportunity for experimenting with totally new ways of organising the production of goods and services. It could, if we are clever, put an element of skill back into some tasks, return the control of pace and pattern of hours of work to the hands of the worker in others, give people a choice of work location (home, office or factory) in yet others, and eliminate many repetitive and dehumanising jobs.

Many new problems will arise of course. For example, there is the difficulty of sustaining the capacity for rapid decision-making in supervisors of computer-controlled plant. They may have to act quickly when unforeseen faults occur, but only at infrequent intervals. Regular sessions on an analogue computer on which faults are simulated might form part of the solution. Another problem is how to develop, retain, and transmit, manual skills which may be required only at intervals. This may turn out to be less of a problem than might appear. It is conceivable that extended use of numerically controlled machine tools and robots will enable improvements to be made to components much more frequently than hitherto, because there will be no need to replace expensive sets of specialised jigs and tools. It may be, therefore, that it will come to be normal practice to engage in fairly continuous product development, which will require the almost continuous manufacture of 'hand-made' prototypes using skilled labour.

Having, we hope, brought the reader to a more optimistic frame of mind, we may conclude this section on AT versus advanced technology by pointing out that the dichotomy is not a real one. Technological development occurs in fits and starts: sometimes one field is affected and sometimes another. Although science can discard outmoded theories when new ones appear, societies cannot so easily discard outmoded technologies because most represent vast capital investments. Our nineteenth century sewer networks are

still with us and, as another example, if a new automobile fuel were to be invented it would have to be capable of being dispensed by the present network of garages. Environmental and ecological protest groups tend to think of AT as a revolutionary solution of technological civilisation's problems, although technology is on the whole an evolutionary pursuit.

In some areas of activity, AT will no doubt be a useful supplement to advanced technology. For example, when the working week is shortened, as the labour force is rationalised and more shift systems are introduced to share out work more fairly, people will wish to involve themselves in both home and local environmental improvement schemes. AT, in the form of special tools and techniques for use by the amateur craftsman, will no doubt find a place in this context. No doubt, too, small wind-generators and hydraulic turbo-generators will be more widely used in sparsely populated farming regions. But our great conurbations cannot be served adequately by windmills, bio-gas digesters, pedal-powered machines and composting toilets, as some advocates of AT seem to suggest. Furthermore, AT may sometimes have as many undesirable side-effects on the environment as advanced technology – it is certainly not always 'non-violent' or 'convivial'. The use of wind power on a large scale could ruin some of the most prized stretches of coastline: modern windmills on a megawatt scale bear no resemblance to the quiet picturesque Dutch variety. Or again, water power has ruined some beautiful rivers in mountainous regions. As a final example, now that our conurbations and transport systems have been modified to suit the motor car, its abolition would cause a tremendous social upheaval. We must conclude that although AT may have a part to play, mankind is likely to be better served by groups who do not overstate their case than by those who allow their strong emotional attachment to a particular life-style to outweigh common sense.

Chapter 6

Control of Technology

Technological decision-making, risk assessment; social control of technology.

The previous chapter dealt with broad categories of technology, and we concluded that advanced technology was here to stay. We have now to consider how more detailed decisions are taken, about which particular projects to pursue to meet given needs. Should we in the U.K., for example, initiate a breeder reactor programme or a Severn Barrage tidal-power scheme to safeguard our power supplies? Should we start district heating schemes using combined heat and power plant to reduce our expenditure of energy on home heating? In view of the wide-ranging social consequences of large projects, which cannot always be foreseen, it will also be important to discuss the means at our disposal for assessing the risks involved.

Finally, although in chapter 5 we suggested that it is impossible to control the search for scientific and technical knowledge, we have not discounted the possibility of controlling its application. In effect this implies consideration of the ways in which society can exercise control over technological projects. In the past such control was very largely left to economic forces.

Technological decision-making

We need not concern ourselves with comparatively straightforward choices between different solutions to technical problems based on a single objective criterion such as an agreed measure of efficiency or economic worth. This kind of choice is made as a result of feasibility studies and 'design point calculations' in the early stages of the design process. In these circumstances, when all the options are known and all outcomes can be evaluated, we have what is called *decision-making under certainty*. Nor need we be concerned with situations where although not all the consequences of the options can be evaluated with certainty, they can be assigned objective probabilities. Economic consequences are often of this kind. We then have *decision-making under risk*. In such cases an objective measure can be optimised using an appropriate brand of mathematical decision theory. Even in difficult cases where there are several decision makers with conflicting interests (that is, competitors), the problem of optimisation is potentially capable of being handled by mathematical game theory. We say 'potentially' because in fact such theory presupposes that all the competitors behave rationally and adopt optimum strategies, which in the practical world is a dubious assumption.

Next in order of complexity is the situation where some of the consequences of the options cannot be assigned objective probabilities. This situation arises when non-quantifiable values are involved in the decision – ethical values and social norms, or subjective attitudes of the public to both hazards and benefits.

This is called *decision-making under uncertainty*. Mathematicians are busily engaged in developing what is called 'fuzzy logic' to provide a rational basis for taking decisions when the information is imprecise[1]. At best, however, such a logic will be applicable only if all the consequences are known. Assessment of the risk to the public associated with a particular technology has been treated as an example of this type of problem. It has assumed such importance in recent years that the next section will be devoted to it. We shall argue, however, that risk assessment is not likely to fall into this potentially soluble category. Rather

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[1] For a good introduction to these ideas see chapter 6 of D.I. Blockley, *The Nature of Structural Design and Safety* (Ellis Horwood, 1980).

that it falls into the insoluble category which Collingridge[2] calls *decision-making under ignorance*. It is this class of problem that concerns us in this section.

'Decision-making under ignorance' arises when we cannot identify all the consequences of an option, let alone assign probabilities to those we can identify. This is the common situation in which our policy-makers find themselves, whether they be in the boardroom, civil service department or parliament. The political, economic, social and environmental consequences of most major technological decisions are now so extensive and diverse that it is impossible to foresee all of them, or to quantify many that are foreseen. Furthermore, it is also impossible to arrive at a quantifiable criterion for saying that option A is better than option B. In this situation, what attitude should be adopted by a rational policy-maker?

Firstly, the rational person will admit the possibility – indeed the probability – of error at the outset. Secondly, he will make arrangements to monitor the effects of his decision. Thirdly, he will respond readily to signs of error by modifying his option. Doctors do this all the time, although it is relatively easy for them because they do not have to justify every action to the patient. But how often does one hear of an architect monitoring the adequacy of his buildings[3]? If the principles are difficult to apply even in such a relatively simple and obvious case, it is not surprising that we seldom find them applied in the more difficult field of technological decision-making. The difficulties are very real even if we discount psychological restraints: that is, even if we assume the existence of ideal, modest, decision-makers, who are not afraid to admit a mistake, faced only with ideal forgiving critics who always remember that hindsight gives problems a spurious air of simplicity. The chief difficulty is that the full consequences of a technology become apparent only late in the life of the technology. By the time they do, the expense of modification is formidable if not prohibitive. Two examples often quoted are (a) widespread use of chemical pesticides that led to the emergence of resistant strains, and attack by new pests because the ecological balance had been upset; and (b) the use of lead-additives in petrol to improve engine performance without foreseeing that widespread use of the car might result in harmful concentrations of lead compounds in the urban atmosphere. In both cases it is difficult to change direction because of the vast capital investment involved: in the chemical industry in the first case, and in both the motor manufacturing and petroleum refinery industries in the second.

With this difficulty in mind the desirable features of a good technological decision are not too difficult to enumerate. Collingridge lists them as follows.

(a) The time which elapses before some performance indicator shows up the error should be short; this is the 'monitoring response time'.

(b) The cost of the error should be small.

(c) The time it takes to introduce a better option should be short; this is the 'corrective response time'.

(d) The cost of reinvesting in the new technology should be low.

To achieve a short response time, the performance indicator should be sensitive; to achieve a low error cost the technology chosen should preferably be an option having a high ratio of variable cost to fixed cost because fixed costs are normally lost if the decision is wrong. In general, a system of small units is easier to correct than a system of large units. This is because with the former it is easier to match supply with changing demand so that errors in forecasts of demand become less important, and also the lead times for new plant are shorter. There should be more consideration given to trading off economies of scale against ease of correction. This is particularly relevant in the electrical power industry, although here the apparent economies of scale have seemed so substantial as to be almost overwhelming. Now that it is possible to work with actual figures of running cost and power production over a number of years, the economies obtained by using very large fossil fuel plants are not so clear-cut.

It is worth remembering that although the initial number of options may be large, the number may decline as the monitoring and corrective response times become longer. This is because the economic benefits have to be that much greater to offset the cost of the error which has been mounting with time. On the other hand, new technological options may have arisen in the meantime, so this is certainly not a general rule.

The factors which lead to decisions being undesirably sensitive to error have been examined in detail by Collingridge, and they may be summarised as follows.

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[2]D. Collingridge, *Social Control of Technology* (Pinter, 1980).

[3]It is not the fault of the architect: who would supply the necessary funds? Such monitoring, however, could be a fruitful source of research projects for the staff of schools of architecture.

(a) Competition increases the error costs: it can lead to an infinite cost if it is a case of a company going bankrupt or a nation losing a war.

(b) Long lead times in a competitive situation mean that decisions to adopt a particular technological option cannot be postponed until the decider sees that his competitor is also choosing that option. Since both competitors think in this way a technology, which both feel undesirable on social or environmental grounds, may nevertheless be developed as a hedge against the worst outcome. Decisions taken as hedges against possible developments in a competitive situation ensure that the competing developments do in fact take place, so that the decisions are self-justifying. Military technology obviously spirals in this fashion, but so do new technologies like microelectronics and robotics.

(c) A technology can become entrenched because neighbouring technologies adjust themselves to suit it. For example, it would be difficult to change the addiction to the motor car because bus and train services have been slimmed down, offices and factories have moved away from city centres, the chemical industry has adjusted to use the residues of crude oil after petrol extraction, oil refineries have been designed to produce the necessary quality of petrol, and there is a vast infra-structure of small industries and garages involved in motor car production and maintenance.

We said that a good decision is one that can be monitored easily. In practice it is often difficult to show that a decision was in error, that is, to falsify a decision. Factors which make it difficult are enumerated by Collingridge as follows.

(a) First there is the reluctance to monitor the outcomes for fear of being shown to be wrong. Extreme forms of this are found in the U.S.S.R., where particular scientific and technological theories can be associated with a political ideology in a rigid bureaucracy. The Lysenko affair was a tragedy for Soviet agriculture.

(b) The books may be cooked in the sense that the objective is altered to suit the results: again for fear of being shown to be wrong.

(c) Some decisions are very difficult to monitor: (i) when doing something positive it is not always possible to say what would have happened if it were not done, particularly in relation to benefits received, and (ii) the objectives may be very imprecise or there may be multiple objectives.

(d) Often the objective is a future benefit, but how far in the future is not specified.

(e) Finally, there is the Catch 22 type of question: people say a technology should be used only when it is shown to be 'completely' safe, yet this cannot be done without developing the technology.

In the light of all these problems we may well ask how any kind of social control of technology is possible. This we will discuss in the last section. Before doing so, however, we will review the special difficulties of an important input to many technological decisions, namely, the balancing of the hazards which arise from the use of a technology with the benefits received. We have to ask ourselves whether this is in principle a soluble problem or not.

Risk assessment

Hazards to life and limb have become a major preoccupation of the developed world in the last few decades for two main reasons – one objective and the other subjective. The objective reason is obvious: the impact of rapidly expanding technologies on an increasingly populated world. For example, our ability to handle dangerous materials has led to the production of a greater variety and to their use on a wide scale. We produce hundreds of new chemicals annually, radioactive isotopes, liquid natural gas and so on[4]. Furthermore, the development of instrument technology to the point where minute concentrations of potentially toxic materials can be measured has stepped up the search for connections between new chemicals and health.

The subjective reason for our recent preoccupation with safety is that we have been so successful in combating natural disasters, such as epidemics and famine, and in increasing the length and quality of life,

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[4]The fact that we also produce all manner of explosives, from 'plastic' to nuclear bombs, is a separate issue: we are not discussing here the ultimate risk – war.

that we value our lives more highly. Perhaps a waning belief in life after death plays a part also. Man-made disasters, widely publicised in the media wherein bad news always drives out the good, now stand out prominently. They seem so much worse than the natural disasters which remain, no doubt because in one sense they are avoidable – we need not have used the technology. This is not a very rational feeling, however, because earthquakes and hurricanes bring no benefits whereas technologies do.

Just as an engineer seeks to design his machines and structures so that all members are equally strong, one might expect society to require that our technologies should be made equally safe. That it does not do so is evidence of a subjective element in risk assessment itself. People readily adapt to the familiar and are fearful of the new. They also take account of the benefits when these are obvious. The motor car, for example, is so familiar, and the benefit of personal mobility so great, that a very high risk is accepted. Insurance is the method used to mitigate the consequences of such risks. Other evidence of subjectivity is the difference in attitude to the death of 100 people in one accident as opposed to the same number spread over time or space, and to a major disaster once in 100 years compared with more frequent minor disasters. Should a community prefer the minor, but statistically certain, losses from periodic floods to the risk of a large loss when a dam, constructed to prevent flooding, bursts? High-risk technologies may involve the use of tighter security measures against possible terrorist activity: will they have a serious effect on the freedoms of ordinary people and, if so, do the benefits conveyed by these technologies compensate for this? There are no simple answers to such questions.

The total assessment of risk involves three separate considerations: (a) the likely frequency of the event, (b) the loss suffered if the event occurs, and (c) the level of risk likely to be acceptable to those affected. It is the third consideration which poses the greatest problem to the policy-maker. When the project is merely a variant of existing activities he can refer to what has been regarded as an acceptable risk in the past. This approach is inapplicable to new technologies such as nuclear power or genetic engineering. Then he may look for some kind of absolute standard. For example, where a maximum permissible level of radiation is concerned he may use the natural background radiation to which all are subjected, plus some marginal dose based on either (a) the additional radiation received by those living in regions of particularly high natural radioactivity, or (b) the average dose received from medical X-rays. Genetic engineering is not yet with us, but one could conceive of a standard of acceptability being set relative to the frequency of adverse natural genetic changes. When what is at hazard is not a matter of life and death, but a desirable environmental value, a cost-effectiveness approach might be used. The acceptable limit could then be where the incremental reduction in risk is just balanced by the incremental cost of risk reduction. This possibility follows from the nature of the curve of risk versus cost of reduction, which is usually of the form shown in figure 6.1 Such an approach is applicable only when the risk can be assigned some monetary value; for example, the cost of property damage and/or health services attributable to a level of atmospheric pollution. When both the risk of the technology and the benefits received can be assigned monetary values a cost-benefit analysis can be used.

This brings us to the question of how the risk is to be assessed. If the probability of the event occurring can be estimated, and the probability that if it occurs a certain loss will be sustained, then the result can be expressed by the kind of graphs shown in figures 6.2(a) and (b). Here we are looking at two kinds of consequence – loss of life and financial loss – and they are kept separate because of the impossibility of assigning an acceptable monetary value to a life. The well-known Rasmussen study of the safety of nuclear reactors presented results in this form. That study is an example of risk assessment which uses a whole battery of mathematical techniques. Fault 'trees' are compiled to show all foreseeable routes to failure, and each failure is assigned a probability from the known behaviour of individual components and systems of components. The *strength* of such an extensive study lies in the way it highlights areas where more data are required, and it can certainly lead to better safety measures being taken. For these reasons it is highly desirable that studies of this kind be undertaken. The *weakness* is two-fold.

Firstly, a comprehensive mathematical study can give the technical people involved a false sense of security. False, because when human error can play a part it is not possible to foresee all possible sources of failure; and, furthermore, it is very difficult to give meaningful probabilities to very rare events. The second weakness is that it is such a complex process of assessment that the concerned public cannot understand it and so distrusts the results. It is only human to regard evidence which supports one's belief as reliable and useful, but that which does not as unreliable and unrepresentative. Opponents of any technology can always argue that extensive safety studies are evidence of extreme danger. It may be so, but sometimes an industry is forced to make them by the public's irrational fears. Such fears are reinforced when minor mishaps are given prominence by the media as a result of pressure from self-appointed watchdogs. The expert's explanation is

inevitably regarded as an expression of a vested industrial interest. This has all the makings of an anarchic situation: a technological equivalent of the state of affairs which exists when unofficial vigilantes roam the streets. How then should we tackle the problem of adequate social control of technological developments? To this we address ourselves in the last section.

Social control of technology

Society has little difficulty in exercising adequate control of well-established technologies through various kinds of regulatory bodies and inspectorates, enforcing orders made by government. There is nothing new in this type of control, and we noted in chapter 2 that an anti-pollution act was passed by the English parliament as early as 1388. This is how the quality of our water supply, food and medical drugs is ensured, and the safety of buildings, ships and aircraft is maintained. Where safety is concerned, the type of action follows the pattern of risk assessment. That is, an attempt is made to control both the frequency of the unwanted event (for example, speed limits and driving tests to reduce road accidents), and the consequences of the event (seat belts and compulsory third-party insurance). In some cases a regulating function can be rather costly to the community. For example, fire officers and factory inspectors may sometimes suggest unduly extensive and expensive changes, to make doubly sure that they cannot be accused of negligence if an accident occurs; and the managers of organisations comply for the same reason. The old question of who is to watch the watchdogs is always with us. But all these orders and regulations are very necessary in view of the propensity for unscrupulous individuals and companies to cut corners in pursuit of the 'fast buck'.

Governments also exercise control in the opposite sense, by stimulating and supporting a technology. This arises when an industry ceases to be of sufficient benefit to its customers to remain economic, but nevertheless the community as a whole finds it of indirect benefit. Then the government directs some of its revenue from taxation to subsidise the industry. Railways have been supported in this way for several decades, and there are good grounds for doing so. Competition from road transport is unfair in the sense that the railways do not have their track and safety systems paid for by the community as are the roads, traffic lights, traffic-police and so on. There is no question in this instance of delaying the modernisation of an industry which is in competition with overseas counterparts. When such competition is involved, indefinite subsidies from the tax-payer will not contribute to the long-term health of the economy: they should be of limited duration to cover only the period of reorganisation and reinvestment (as in the British car industry).

So much for the means of controlling traditional practices. The problem is a little more difficult where the control of a new technology is concerned. This is because in the early stages the only individuals with sufficient expertise to act as inspectors are employees in the industry. Although some will be enticed to work for the new inspectorate, inevitably their independence will be questioned. Furthermore, in a rapidly growing high-technology industry, like nuclear power, the inspectorate will be dependent to some extent upon information from the industry. The close working relationship required may lead to accusations of bias in favour of the industry. It goes without saying that the regulatory body should be independent even of any government research establishment set up to support the industry: this has been the case in the U.K., but not always in the U.S.A.

When it is a question of whether to develop a new technology or not, the problem of control is different in kind. We have seen in the previous two sections how difficult it is to make and monitor decisions about major technical projects, with all that it entails in the way of risk assessment. And we saw in the previous chapter that different sections of the community will give quite different weight to the various social, political, environmental and economic values involved in the decision. One essential step is to make sure that the final arbiter – the government – has a clear statement of the technical issues and their social implications. This can be achieved if a panel of experts, not all of whom are committed to the project, act in an adversarial way before a Royal Commission, Select Committee of Parliament or Committee of Inquiry. The public need not fear that the experts will inevitably agree. All scientific controversy is about interpretations of so-called facts. Scientists and technologists are quite used to disagreeing with one another, and they can do this without clouding the issues with accusations that the other side has a false set of values and ulterior motives which politicians are prone to do.

Consider the controversy about whether or not to build a commercial fast breeder reactor. The decision will rest on a wide variety of assessments of: (a) the size of uranium reserves, (b) energy demand, (c) the likelihood of other sources of energy becoming available, (d) the importance to be placed on self-sufficiency

in power supply, (e) comparative risks and public acceptance of them, and (f) the desirability of keeping an industry in being for possible future needs. Finally, the decision will take account of our inability to make such assessments with any real accuracy. For this reason we must also make second-order assessments as follows. We must decide which is likely to cause the greater chaos: to have too much or too little electrical power, to let the nuclear power industry decline or support too much of it, and so on. A committee set up to enquire into this problem will try to decide whether the available assessments are the best that can be achieved with the current level of technological and sociological knowledge, and this will involve interpretations of facts and evaluation of probabilities. Only when trying to decide what final conclusions can be drawn from these assessments should views about competing non-quantifiable values and life-styles impinge on the discussion, and these will ultimately be a matter for parliament itself as the elected body representing the majority view.

Whatever system is used for investigating technological options it is important to separate, as far as possible, arguments about ways and means from arguments about value systems and life-styles. It follows that if pressure groups are to be effective they too must be clear about this distinction. In the initial stages, when trying to get the need for a committee of inquiry established, a pressure group can be forgiven for using emotive language, for presenting speculations by scientists and technologists as facts, and for using dramatic statements taken out of context to capture the headlines. Once the inquiry is set up, however, if the group wishes to retain its credibility it must be seen to be keen to elicit as much objective information as possible. The government, needing the facts for its decision-making, should expect to pay for the panel of independent experts used including those called by the pressure group. The pressure group, on the other hand, should spend its money *after* the inquiry – on mobilising public support for the particular environmental or social values it is espousing in contrast to those (which often include an economic value) with which it is competing.

All this sounds simple on paper, but difficulties arise from the inability of non-technical members of parliament or of the pressure group to understand the qualifications which always accompany the results of technical studies. Such qualifications stem from the assumptions made in the course of the studies. There are no simple unambiguous answers to such questions as: 'What concentration of lead in the atmosphere will not endanger health?'; 'What ozone depletion due to fluorocarbons from aerosol cans can be accepted?'; 'What level of oxygen in a river is necessary for the support of fish life?'. Governments have the difficult task of deciding whether to disrupt an industry, perhaps at great cost to the country (that is, to the taxpayer), to meet the arbitrary limit which the scientist or technologist is forced to specify, against his better judgement, by the non-technical people involved.

In the end a government has to strike a balance between no-quantifiable environmental and social values, and relatively straightforward economic values. Sometimes attempts are made to assign a monetary figure to a non-quantifiable value in a cost-benefit analysis, but except in very simple situations so many assumptions have to be made that the exercise is hardly worthwhile. The main objection to quantifying the unquantifiable is that in doing so the environmental or social value is stripped of much of its essence. Cost-benefit analyses may lead a government to look for what is *efficient* for society when really it should be looking for what is *good* for society. Such analyses may sometimes help us to find the most efficient means to a chosen end, but should never be used to determine the end. Ultimately there is no substitute for wisdom: ideally, the political system should be designed to throw up decision-makers who are both intelligent, and morally sound in the sense that they should be responsive to the changing goals and moral standards of society. When too many judgements are found to be faulty, a democracy has the remedy in its hands,

It should be abundantly clear from this discussion that many, if not most, of our decisions are bound to seem wrong with hindsight. This must be so in any developing society, where not only technology but social and ethical ideas are changing with time. And this is the main argument for the plural society, consisting of relatively autonomous institutions, as opposed to the monolithic society. We need to experiment with both our ethical decisions and our technological decisions. Decisions taken centrally ensure that mistakes affect the maximum number of people. We need thriving local government, local unions, and local pressure groups, together with a tolerance of others who do not think as we do and who have different needs. Tolerance, based on the certain knowledge that the whole truth will not reside in one point of view, is essential if healthy argument is not to degenerate into social chaos. Without tolerance the plural society is impossible. Supporters of the monolithic society, on the other hand, seem to be prepared to sacrifice far too much for the mirage of 'equality'. Human life is so various that one can never assume that every member of society wants and needs the same things.

Even if it is the more practicable 'equality of opportunity' which is sought, rather than equality as such, – and no one would deny its desirability – it is still too impossible to achieve in any absolute sense to make it

worth using means which would jeopardise other equally desirable social ends, such as liberty. To appreciate the difficulty, one has only to think of the genetic component; the varied ability of parents in bringing up children; and the natural tendency for people with similar ability, outlook and achievement to group together and stimulate each other. After nearly two thousand years of Christianity it should not be necessary to remind ourselves that envy is to be deplored and that charity is not to be despised. Few human beings get through their span of life without accepting help from others. One should be prepared to accept a measure of inequality provided it is tempered by responsible and charitable behaviour on the part of the well-endowed.

Finally, we have been concerned in this chapter with what in one sense are 'restrictive practices'. Necessary though regulations may be for society as a whole, governments should positively encourage new developments by sponsoring industrial estates where small concerns can experiment with new ideas free from restrictive labour and safety regulations, and free from the influence of conservative trades unions. There will always be those quite happy to take a risk for the excitement of being first in the field, and society can only gain from such enterprise. This is where a new generation of jobs can come from. No society will prosper if it stifles its innovators – its industrial 'mountain climbers'.

Chapter 7

A Summing Up – and Speculation

Summary

Although in this book we have been trying to make explicit the distinctions between engineering and other forms of knowledge, one must beware of thinking that there are necessarily any hard-and-fast distinctions. Real life cannot be pigeon-holed neatly. It is more correct to think of a continuous spectrum of any particular characteristic over the range: art, craft, technics, technology, engineering science, science, and so on. This is why the reader will from time to time have said to himself ; 'Surely this is also true of some sciences' or 'That surely applies also to some technologies'. But the fact that we know light to be a continuous spectrum of frequencies does not prevent us from finding the crude concepts of red, blue and green very useful. Making distinctions is what we do from birth: our sight separates out colours and shapes, and our ears isolate sounds, in what the electronic engineer would call the 'noise' of the world around us. Furthermore, we coin words to express these distinctions so that we can communicate our experiences to each other. This is what the development of language is all about. With this warning out of the way, let us try to summarise the important distinctions we have found.

The fundamental presupposition upon which engineering is based is that our environment can be controlled and modified. This idea was historically prior to the fundamental presupposition of science, which is that the human mind can hope to understand the world around us because of the regularity exhibited by natural phenomena. The reason is that the latter idea needed the development of a reasonably sophisticated language before it could bear fruit. These successive presuppositions served to liberate man from the feeling that he was totally at the mercy of fate.

The impulse to modify the environment led first to craft. The process of development consisted of: (a) a craft being invented to meet a perceived need, (b) new needs arising which could be served by that craft, and (c) these new needs stimulating development of the craft and sometimes the birth of a new craft. Eventually bodies of knowledge consisting of rules-of-thumb were compiled for each craft and something we called technics arrived on the scene. Finally, when logical reasons were found for these rules-of-thumb, and coherent theories were established to explain them, technologies were born. Before this stage had been reached, the observations, speculations and classifications of phenomena by natural philosophers had been supplemented by controlled experiments. This led to the formulation of theories from which experimentally verifiable predictions could be deduced and we had the beginnings of science. We were then enabled not just to describe natural phenomena but to explain them.

The success of all this activity depended upon specialisation, and in particular upon the ability of agricultural communities to create food surpluses to support craftsmen and scholars. In return, science and technology have been applied to agriculture to maintain the situation.

We have observed that science and technology are now completely dependent upon each other. The dependence of science upon technology came first. There was the direct dependence on technology for the supply of apparatus and measuring instruments, and for paper and printing to aid the exchange of ideas. There was also an indirect dependence in the sense that the activities and inventions of the technologists threw up stimulating questions to which science was able to find the answers. Following the rapid rate of growth of the sciences, technologies came to depend on them more and more for their own improvement, and now much new industry has sprung directly from important scientific discoveries. The rapid growth of science stems from the fact that the scientist is relatively free to follow his nose. Technologists, on the other

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hand, are constrained by a large number of factors: by economics, because of the large capital investment involved in industry; by the need for caution owing to the risks involved; and by ethical considerations because of the widespread effect of their activities upon society. Technology is essentially an applied activity and it is easier for society to restrain this than the search for scientific knowledge.

From our discussion of scientific explanation of phenomena, we were able to see the limitations of science. Essentially science involves theories which describe the 'how' of things, and which enable us to predict future events in prescribed situations. These theories make use of abstract concepts which do not necessarily have a one-to-one correspondence with anything in nature. Technological explanations can be of a rather different type, varying from the teleological type of explanation used in historical studies to scientific-type explanation. The purposes of scientific and technological explanation are very different. In the former, the establishment of better theories is paramount, while in the latter it is improvement in the efficiency of our products and constructions. This difference in purpose is reflected in a different attitude to accuracy. Accuracy is vital to the scientist because it can decide which of two theories is to be preferred. It is of less importance to the engineer or technologist because of the variable and imperfectly known conditions under which his constructions will have to operate. Technology makes use of so-called laws, which differ markedly from scientific laws. It makes sense to ask whether the latter are true or false, or under what conditions they are true. In technology it usually makes sense only to ask if they are sufficiently accurate for the current application.

We illustrated the difference between a scientific subject and a technological subject by describing the way thermodynamics differs from engineering thermodynamics. As a result we found it useful to make a distinction between technology and engineering science. Technologies are classified on the basis of the industries that they serve, whether they be product or materials technologies. This is very different from the way the sciences are classified, namely, on the basis of the type of natural phenomena being studied. The engineering sciences are so called because they are classified on the basis of the type of 'unnatural' phenomena studied; for example, the way fluids behave when constrained to move in various ways by our machinery.

No doubt because of the fundamental role of design in engineering, there is a tendency for engineers to refer to the 'art' of engineering. We examined the nature of art to see if engineers were using the word in anything other than a very loose way, and were forced to conclude that they were not. In so doing, however, we clarified our ideas about craft, and we were able to see what creativity means in engineering and distinguish it from creativity in art and science.

It follows from the essentially applied, and public, nature of engineering, and its profound effect upon the way in which we live, that ethical problems are bound to arise from its pursuit. (Because science and technology are now inextricably interwoven, in one sense this is also true of science: but strictly speaking it is the application of science through technology that gives rise to its ethical problems.) We discussed ethical problems associated with our attitude to future generations, to our own lives, to the Third World, and to our environment. We noted that these problems are quite different in kind from those of science and technology, in that they are perennial problems which have to be answered anew by each generation. The broad categories of 'advanced' and 'alternative' technology were compared. It was concluded that, with the current level of population, we could not afford to dispense with advanced technology if we wished to give acceptable answers to our ethical problems. The difficulties involved in making detailed technological decisions were discussed at length, as was the associated problem of the way society could control technology. Given the probability of error, we saw the need for humility, and a willingness to monitor our decisions. Finally, we ended with a plea for the 'plural society' to minimise the effect of error, and for 'no-regulation' areas in which the spirit of industrial adventure can flourish.

Speculation

We have now reached the end of our attempt to delineate the main features of one of man's important preoccupations technology. What we have not pointed out, however, is that unlike some of his other preoccupations, such as art and religion, technology is not an end in itself. No doubt for some technologists it is, and in so far as it has its roots deep in the evolutionary process (we are not the only tool-using animal) it is certainly as fundamental to the nature of our species as any other pursuit. But no one has yet suggested that the object of the universe – if it has one – is the development of a species that can alter it.

Most reflective people would regard technology primarily as an aid to providing an environment in which

a man's brief span of life can be lived fruitfully in dignity – in which he has an opportunity to develop those characteristics which make him truly human. A philosophy of technology is bound to concentrate on one of his characteristics – that of being a tool-using animal – but he is very far from being just a tool-using animal. One has only to consider his achievements in understanding the physical and biological world through science; the expression of his feelings about the world through his art, poetry and music; his reflections on the mysteries of life through his philosophies and religions; and his attempts to wrestle with human relationships through literature and psychology. Technology gives more time to more people to engage in these life-enhancing activities, while itself being a fascinating pursuit for those whose talents lie in that direction. That we have yet to find a way of harnessing technology for the greater benefit of mankind rather than for the favoured few is not surprising. Even in historical time – let alone biological and geological time – the life of technological civilisation is very short (figure 7.1). It is surely not utopian to believe that we will eventually make a breakthrough that will release fresh energies and lead to new hope for the poor and oppressed: certainly to give up the attempt is to cease to be human.

The breakthrough will not arise simply from acts of a political nature; it is not a question of substituting socialism for capitalism for example. Our problems are certainly deeper than that. Nor is it sensible to look for a resurgence of religious faith. Such resurgence would simply add yet more divisive factions to the scene, because to proclaim one creed is simultaneously to deny all the others. To see where one might look for a hopeful sign, let us review briefly a possible explanation of the origin of religious feeling.

In *homo sapiens*, consciousness has developed to the point where life cannot help asking about the meaning of itself. Man cannot fail to wonder why he is here and what his role in the universe should be. Furthermore, he is disturbed by his failure to answer such questions. He is disturbed because rightly or wrongly he feels responsible for his actions. (If he did not believe in free will, ethical concepts would never have arisen.) The first reaction of mankind to the riddle of life was to people nature with gods and ultimately to transform this pantheism into sophisticated religions. The Christian concept of Incarnation and Atonement is a symbolic expression of man's need to be absolved from his feeling of guilt at not knowing what he should be doing or, in religious terms, at being estranged from God.

The second reaction to the riddle of life was to try to find out by scientific endeavour how the world works. But this led first to the dethronement of planet Earth via the Copernican revolution, and then via Darwinian natural selection to the dethronement of man as a unique creature. Man was left with the feeling that all was accident and there was no purpose to his existence. On the material plane, science has also brought man to the brink of extinction by his own efforts. Can he possibly correct the destructive elements in his nature before his atomic weaponry destroys him?

There are two grounds for optimism – one is psychological and the other physical. Firstly, recent advances in biochemistry and biology may throw up an acceptable explanation of the origins of life and species[1]. This could lead to a climate of ideas which would renew man's sense of purpose, restore his psychic energy and promote a social cohesion that is so sadly lacking. For too long people have been saying that either there is a god with a divine purpose for humanity, or we are an accident with no purpose whatever. We may find the truth lying close to the underlying meaning of the religious view, even though some would say that it is couched in mythological terms. Certainly there appears to be something purposive about evolution. We should be neither surprised nor dismayed that we have as yet no answers to these fundamental questions. Man is a very late development indeed. If the age of the earth is scaled down to one year, man appeared at about 10.00 p.m. in the evening of the last day. And on this time scale he has been solving problems scientifically, that is, tentatively on the basis of evidence, for little more than one second.

The other ground for hope lies in recent discoveries in genetics. There is now a possibility that man will acquire the ability to eliminate genetically transmitted diseases. In so doing we may find that his propensity for self-destruction is modifiable also. We are talking here about a new form of engineering – genetic engineering. When techniques for making positive and desirable genetic variations are finally established, man will certainly employ them to improve himself, just as he has used random variations to improve his livestock and plants. It will be another of those developments which are accelerated by competition between nations. Any society which eschews it will be at a serious disadvantage. Genetic engineering will bring in its train the most serious crop of hazards and ethical problems that mankind has had to face. If we are to have adequate time to devise appropriate safeguards it is not too early to begin to debate these matters

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[1]Contrary to the belief of 'creationists', recent developments in palaeontology do not contradict the concept of evolution, but merely the original idea of it as a steady process of small random variations some of which are adapted to changes in the environment. Evidence now accumulating confirms that life has also evolved in discrete jumps by rather large genetic changes – mutations – the cause of which is still uncertain although the mechanism is understood.

at a serious level. There will, of course, be those who see nothing but fear and horror in the prospect, no doubt as did some early groups of humans when faced with the prospect of the controlled use of fire.

Ordinary engineers and technologists have a vital part to play in this voyage of discovery: not only in providing specialised equipment for the voyage, but in solving the more mundane problems involved in keeping the ship fuelled and the crew victualled.

Only then can our geniuses concentrate on the navigation.

Back Cover

This book is a contribution to the debate about the profound impact of technology on our lives, the ethical problems arising therefrom, and the ways in which society can exercise control. In a democracy, such control is likely to be effective only when the public, civil service and politicians have a clear idea as to the nature of engineering and of the conditions under which new technologies develop.

The author contrasts the history of technology with that of science, and highlights the essential features of technology in relation to other forms of knowledge. For this reason the book has been subtitled 'A Philosophy of Technology'. This approach enables our current concerns to be seen in perspective, and helps the author to discuss the less factual material with some hope of objectivity. He is neither a utopian nor a prophet of doom. Those who feel alienated by advanced technology should be reassured by this book.

The aim has been to state the problems clearly and concisely to stimulate discussion, and the book will be useful to engineering students preparing for their paper on 'The Engineer in Society'.

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