# THE INTERNAL STRUCTURE OF TECHNOLOGY

*R. D. Johnston*

'No social, human, or spiritual fact is so important as the fact of technique, in the modern world' (Ellul, 1965). Certainly technology is a pervasive and ever-present element of modern life. Equally certainly, it has been, and continues to be, the subject of intense interest within the framework of many different disciplines.

Economists have come to regard technological growth as the major basis of economic growth. This has led social scientists of many persuasions to examine the development of technology in industry with the aim of optimising the process.[1] It has also stimulated analysis and prediction of the forces operating on industry and society due to the imperatives of technology. (e.g. Galbraith, 1967). Existential philosophy, as exemplified by the writings of Karl Jaspers (1951) has viewed precisely this increase in material welfare as a threat to 'true individuality'. More recently many social critics have condemned technology as a source of dehumanisation and political domination.[2]

Despite this intense interest and study, Ellul is able to continue: 'And yet no subject is so little understood.' This lack of understanding is exemplified by the frequent confusion between science and technology. Though these terms obviously represent different forms of activity, with different aims and different limitations, it is not uncommon to find discussions of technology to which are ascribed the properties of science. The fact that science and technology are frequently closely related does not preclude an examination of technology in its own right.

The focus of most of the studies of technology has been on external factors relating to its growth. While it is apparent that the growth of technology is considerably affected by market forces, social and economic needs, and available resources, the importance of these factors does not deny the existence of an internal dynamic which also plays a major rôle in the development of technology. It is the purpose of this paper to make an initiating step towards an understanding of the internal structure of technology. It is only with the knowledge of this internal structure, and the way in which the external factors impinge upon it, that a coherent model, and hence control, of technology can be developed.

*Technology as a System of Knowledge*

Technology has long been an appropriate subject of study for historians by one of two principal methods; the first is characterised by a concern for the piece of hardware in itself, which has been called the 'antiquarian' approach (Cardwell, 1967); the second is the economic historian's approach, in which the interest in technology extends only to its impact on the economic growth of the community. Neither of these methods provide an understanding of the theoretical and conceptual bases of technology. Cardwell (1967), in laying out his framework for the academic study of the history of technology states that 'The history of technology is, therefore, concerned with ideas at all levels' and hence a satisfactory history of technology must describe the emergence, interaction, and diffusion of ideas with technology as their focus. Those who have considered technology simply as a collection of artefacts may be guilty of the same kind of 'misplaced concreteness' (Whitehead, 1926) as that of the bibliometricians of science who have tended to confuse the scientific body of knowledge with the external observables of scientific papers.

There have been a number of attempts to examine the nature of technology and to distinguish it clearly from science. Popper (1968) in his development of a general model of scientific explanation has posited that the pure theoretical sciences aim at the discovery and testing of general laws whereas the applied sciences or technology aim to elicit the initial conditions which in conjunction with known laws will yield desired final conditions. However, as Skolimowski (1966) has shown, such an equation of technology with computation rules does not allow for technological progress, particularly the historically observed progress in advance of and independent of scientific law.

Agassi (1966) has described technology as consisting of a number of elements, among them applied science and invention. Focussing particularly on the latter, he demonstrates that corroboration is important to technological invention, because being 'a theoretical rather than a practical activity' it has to demonstrate that it can do successfully something specified, whereas for science corroboration is unnecessary.

Skolimowski (1966) examines the difference between science and technology in terms of the concept of progress. Thus progress in science results from 'the continuous improvement of scientific theories and constant enlargement of the scientific store', whereas 'It is a peculiarity of technological progress that it provides the means (in addition to producing new objects) for producing "better" objects of the same kind'—a criterion of relative efficiency. That the aims and methods of science are different from those of technology is not a point of controversy here, but the rôle of corroboration or the form of progress would appear to be single elements which must be accounted for by any general theory of technology, but which on their own do not provide an adequate basis for an understanding of technology.

Bunge (1966) has suggested that technological theories may be classified as two kinds. A theory having a bearing on action towards the attainment of practical goals 'because it provides knowledge regarding the objects of action' is classed as a substantive technological theory; such theories are regarded as application to nearly real situations of scientific theories; 'thus a theory of flight is essentially an application of fluid dynamics'. The other class of theories are operative, concerned with action itself, and describe the 'operations of men and man—machine complexes in nearly real situations'. Theories of value, decision, games and operations research fall in the operative class. Such a classification of technological theories may be of use in constructing an epistemology of technology, but to fail to realise that technology is composed of more than theories would be to walk into the same blind alley from which the epistemology of science has only recently escaped. In what sense then can technology be considered a system of knowledge? Clearly it is not a body of systematic knowledge comparable to that of science. Whereas the professed goal of the scientist is the extension of scientific knowledge, the goal of the technologist is to produce in Gold's terms (1969) an increased capability for man. Hence there is little conscious effort on the part of technologists to systematise their knowledge for this is not their direct goal. However, it is equally apparent that when confronted with a technical problem, the technologist does not search for potential solutions on the basis of first principles. He has a set of guiding principles composed of elements of scientific law, technological 'know-how', and previous practice on which to draw. It is the essence of these guiding principles which form the basis for treating technology as a system of knowledge. There is a need to examine these sets of guiding principles, the elements they are composed of, the way in which they are modified over time, and the ways in which they are transmitted from generation to generation of technologists. The answers to questions like these may provide a far more suitable basis for constructing a model of the internal structure of technology than any consideration of artefacts.

*Kuhn and the Concept of Paradigm*

The study of the development of scientific thought has undergone a major reorientation during the last decade as a result of Thomas Kuhn's *The Structure of Scientific Revolutions*, the thesis of which is too well known to require detailed exposition here.[3] It is proposed here to examine Kuhn's general view of science in order to determine whether any of his constructs could be of value in developing a theory of the internal structure of technology.

From the contention that the generally accepted view of scientific progress by incremental accumulation of unit pieces of knowledge is a fundamental misconception propagated by scientists, Kuhn is led to a rejection of Popper's (1969) view of science based on the falsifiability principle. The majority of basic scientific research is described as 'normal science' consisting of 'puzzle-solving', oriented not to the testing of theories or to the pursuit of fundamental discoveries but rather to the determination of solutions of expected types to prescribed problems according to standardised procedures, success being limited only by the ingenuity of the scientist. The notion of a 'paradigm'; the 'accepted examples of actual scientific practice—examples which include law, theory, application and instrumentation together . . . models from which spring particular coherent traditions of scientific research', is that which provides the moulding force to standardise scientific endeavour in this way. Thus a paradigm may well be considered as synonymous with or at least a component of Polanyi's 'tacit knowledge' (1966) which constitutes the backbone of the scientific tradition to which new procedures and ideas are usually compared. The adoption of the paradigm as the central unit of analysis represents a major shift of focus from the usual analytical items such as theories or laws to the holistic set described above.

Within the bounds of normal science, research is narrowly focussed, but it is only under these conditions that rapid exploitation of the paradigm with a minimum of dissension can occur. Under certain conditions, not clearly specified by Kuhn, the emergence of anomalies can provoke a crisis which is resolved only by the emergence of a new paradigm. The revolutionary process of paradigm-change is not a rational one. According to Kuhn competing paradigms are psychologically 'incommensurable', the comprehension of the new paradigm requiring a 'gestalt switch'. Also the initial acceptance of the new paradigm is based on its resolution of the anomalies and perceived improved puzzle-setting potential; obviously non-cognitive factors may be important in such a switch.

The single concept central to this view of the growth of scientific knowledge, and perhaps largely responsible for the wide interest in this work, is that of the paradigm. This term, in the sense of a model or pattern is of course not new to philosophy. But the way in which Kuhn invests it with socio-psychological characteristics is novel, for the paradigm is not only a cognitive framework within which the scientist studies nature, but also acts as a norm, adherence to which is a condition of membership in the group recognised by other scientists as making a valid contribution to a particular field of science. Kuhn, in developing this concept admits a certain circularity in his Postscript (1962) in which he states: 'A paradigm is what the members of a scientific community share, *and,* conversely, a scientific community consists of men who share a paradigm.'

The concept of a paradigm, though of great intuitive appeal, has also been the source of much criticism on account of the ambiguity in its use by Kuhn. Masterman (1970) has extended herself to detect twenty-one different senses in which it is used, but condensed these into three main groups: metaphysical paradigms which cover sets of beliefs, standards and organising principles governing perception; sociological paradigms, which are universally recognised scientific achievements; and artefact or construct paradigms which are of a more concrete sort, including text books, tools, and actual instrumentation. Mulkay (1969) has also examined this ambiguity in the use of the term paradigm and the lack of a clear distinction between the paradigm and the derivative (as claimed by Kuhn) scientific rules, and suggested that they may be profitably replaced by the sociological concepts of cognitive norms and technical or methodological norms. He has emphasised the difference in the centrality of cognitive and technical norms and by implication suggested that scientists will adhere to the norms or paradigms to varying extents. Feyerabend (1970) has criticised Kuhn's monistic paradigm view of science and from an examination of various fields of science concluded that many paradigms are in operation in any field at one time.

A pluralistic modification of Kuhn's concept of a paradigm would posit the existence of an inter-related set of paradigms operative in any field, and allow for paradigms having different degrees of centrality or adherence. It is proposed to use the concept of a paradigm, in this modified form, as the basis for an analysis of technology in terms of its internal structure.

*Paradigms in Technology*

In the context of this paper a technological paradigm is a set of guiding principles generally accepted by practitioners in a particular field of technology. It is composed of elements which correspond to Masterman's (1970) three types of paradigms, discussed previously. Thus there are sets of beliefs and principles including relevant scientific laws. Also subsumed within the paradigm, but not identical with it, are exemplars. These are the models which demonstrate the functioning and the success of a paradigm. The term is most commonly used to refer to the first artefact representing the new paradigm. Thirdly, there is the body of techniques, and experiences based on previous practice.

The paradigm is an epistemological concept in that it provides a guiding framework for the development of technology. Not only does the paradigm suggest appropriate routes to the solution of technical problems, but it also largely defines what will be recognised as a technical problem. It is also a sociological concept; membership of the recognised community of technologists is dependent on adherence to the prevailing set of paradigms. Adapting King (1971), the paradigm may form a basis for the understanding of the rôle of authority in technology. The paradigm is also a psychological concept for the technologist will tend to perceive the world through this framework, and organise his sense-data to conform to it.

Thus while it is clear that there is a cognitive element in the acceptance of a paradigm by the practitioner of technology, it is not a question of cognitive evaluation alone. Paradigms also act as professional norms for technologists, in that they delineate the accepted type of solution to a class of problems. The knowledge which is gained in the process of becoming experienced in a particular field is precisely an appreciation of the guiding paradigms relevant to the field. Solutions to problems which do not conform with the current paradigm will characteristically be regarded with suspicion, their proposer with hostility, and both be rejected. The attitude of practical men to 'crazy inventors', (cf. Ziman, 1968) provides an extreme example of the action of these norms.

It must be emphasised that a paradigm is a directing factor primarily for the community of technologists involved in developing new technology, rather than for industry, or indeed other groups, which use the outputs of technology. Thus, if progress in technology is seen as the expansion of man's capabilities, either by the development of artefacts with new capabilities or artefacts which produce old capabilities more efficiently, in the widest sense of the word, then it is the action to produce these advances which is largely directed by the prevailing set of paradigms.

A detailed examination of modern technology reveals that much of the activity of producing artefacts representing new or improved capabilities can be considered to be paradigm-bound, and many of the innovations which are commonly accepted as landmark events in technology possess the characteristics of paradigm shifts. The data to support such a hypothesis could be expected to be found within the domains of the history of technology. However, the preoccupation of these historians with pre-twentieth century, and predominantly mediaeval technology means that there are few data available, as it is only in the twentieth century that the community structure of technologists has emerged, and the control effect of a paradigm is dependent, at least to a large extent, on the sanctions of such a community. Moreover the existence of paradigm-bound technology may not be obvious from a reference to the history of technology, as the focus of this history is characteristically upon the major innovations which within this model represent paradigm changes.

A brief reference to the history of the technology of electronics will serve to demonstrate the existence of paradigm-bound technological progress. The invention of the vacuum diode by Fleming in 1904 is usually considered to have ushered in the real era of electronics and this device, when explained by De Forest, acted as the exemplar about which the thermionic valve paradigm emerged. This paradigm was made up of elements including the then current understanding of the nature and properties of electrons, experience with cathode-ray tubes, the knowledge of electron emission, and the techniques for production of evacuated vessels and the selection and forming of suitable emitters. Within this paradigm, the development of improved amplifiers continued for at least thirty years, highlighted by the development of the triode in 1906, the tetrode in 1919, the pentode in 1926, with contemporaneous improvements in emitting materials, from metals to atomic film emitters to metal oxide emitters. The discovery of the transistor effect in 1948 provided the exemplar for a new paradigm which replaced the valve paradigm, and as development continued within the new paradigm, the contact transistor was followed by the junction transistor in 1949, the junction-transistor tetrode in 1952, and the diffused-base-transistor triode in 1954, and there was continual development of techniques for growth of pure crystals and doping. It is only recently that a new paradigm centred on monolithic integrated circuitry has emerged. It is of interest to note that these three successive paradigms have been the basis for distinguishing generations of computers (Rosen, 1969) indicating both the widespread influence of the paradigms and the recognition of the qualitative difference of these three types of developments.

As with science a mechanism exists whereby paradigm-shift can occur. However, in contrast to Kuhn's view of science, there is no crisis of failure involved in the emergence of a new paradigm. Rather, there is a limit to which the exploitation of a paradigm can be carried out before a law of diminishing returns with respect to technological progress appears to set in. When this plateau is reached, there may be for a varying period of time little progress in the field. Then, often as a result of some kind of pressure, whether economic or societal or a combination of these, there emerges a radically new type of solution which provides the exemplar around which the new paradigm is built. Thus in the previous examples drawn from the history of electronics, military and aerospace industry requirements of miniaturisation and also computer industry requirements of reduced time-lag in circuits provided the stimulus for the continual improvement of valve technology, and subsequently when improvements on valve technology had reached something of a plateau, in the rapid acceptance of the new paradigm based on the transistor effect.

Paradigm-shifts in technology can be classified into three types according to the mechanism of change. While there does exist a significant pressure to work within paradigms, it has been recognised that once a paradigm is approaching full exploitation, a paradigm shift can lead to a remarkably new kind of technology. This situation provides a description of the technological element of innovation, which has been the subject of a great deal of interest and study recently.

The first of these types of paradigm shifts occurs as a result of the transfer of a paradigm appropriate to another technology, and is perhaps one of the most common forms of paradigm-shift in technology. It can be suggested that the process of technology transfer and the current view of its occurence 'by agents rather than agencies' (Burns, 1969), are illustrations of this first kind of paradigm-shift, An individual, in the process of becoming enculturated in a particular set of technological paradigms, encodes his knowledge and the information received from the environment according to these paradigms. On moving from one area of technology to another, initially he retains the paradigms appropriate to the previous field, and will perceive and interpret problems, and potential solutions, in terms of this previous set of paradigms. No doubt this frequently leads to non-feasible solutions to problems and in order to succeed, the initiate will learn the appropriate paradigm structure by mimesis (cf. Polanyi, 1964) and by formal instruction. However the degree to which the individual technologist internalises these paradigms will vary considerably and occasionally this adherence to another paradigm can lead to a radical new development of the type which may form the basis for a new paradigm. An example of this type of paradigm shift is the development of fuses for the protection of semi-conductors by English Electric, in which a technician with experience in printed circuitry and photo-etching techniques perceived the problem of manufacturing fuses to a very high tolerance in terms of his printed circuit paradigm and adapted these techniques to provide a radically new solution to the problem (Langrish *et. al.*, 1971).

An examination of technology within this paradigmatic framework does not lead to the view of technology as 'an assemblage of pieces of information which can be extracted or expelled from some sector of organised creativity, and transposed to another to produce different outputs'. (Burns, 1969), and this may act as a more suitable basis for the examination of technology transfer. It also provides an explanation for the value of the consultancy rôle in problem solving, not only because of the particular knowledge the consultant possesses, but also because he will view the problems within a different set of paradigms.

The second type of paradigm-shift occurs when individuals who have been made aware of a problem but who are ignorant of the paradigm of technology, suggest radical new solutions. This type may be a subset of the first, in that the solution may well be the result of the application of the universal paradigm often referred to as commonsense. Nevertheless, it appears to occur so frequently that it is worthwhile to make the distinction. Stories are legion of the failure of teams of experts to solve a problem, a satisfactory solution of which is supplied by the cleaner or lavatory attendant. The size-reduction, necessary to the successful innovation in the Petter's marine diesel engine could not be achieved by experts, but a technician without engineering design experience was able to perceive a solution readily by changing the cylinder shape from long and thin to short and broad. (Langrish, *et al*, 1971).

The third general type of paradigm-shift may occur as the result of the emergence of new scientific knowledge which impinges on the laws, theories, and techniques contained in the technological paradigm. However, it must be noted that a change in the scientific theories relevant to a particular technological paradigm does not require that the paradigm necessarily be supplanted. A paradigm is of value because of its success in providing a framework for the useful exploitation of an exemplar, and its truth content is not an object of interest, except in so far as this may limit the range of exploitation. Thus the recognition of the dual nature of light had no effect on the paradigm concerning the technology of optical devices as a shift from a corpuscular to a wave theory of light would not lead to better or more efficient optical devices of that type. But it did result in the emergence of a new technological paradigm based on exemplars of the use of the diffraction effect.

This example serves also to illustrate the fact that technological paradigms never become invalid or are overturned. When the exploitation of a paradigm has reached its plateau, that paradigm remains valid for that field of technology and that technology may remain useful for some purposes. As mentioned previously, it is not the use of a technology which is directly affected by a paradigm shift, though inevitably there will be an indirect and long-range impact, but it is technological progress which is directed by the emergence of a new paradigm.

Given that paradigm-shifts occur, it is necessary to examine the criteria used by the individual technologist to determine his choice between the competing paradigms. As with science, it is evident that no process of comparison and evaluation at *all* points takes place. Also when a new paradigm emerges the hardware resulting from the solution of technical problems within the new paradigm is still in a very crude state, and is usually inferior to products of the old paradigm. Thus in 1952, a review article (Morton, 1952) could still sum up transistors as being difficult to design from theory, tedious to manufacture from design and unreliable once produced. Nevertheless the transistor paradigm, consisting of elements of the quantum theory of conduction and A. H. Wilson's classic work on conduction in semiconductors, the understanding of the 'injection effect', metallurgical techniques of high purity crystal growing and doping, and of suitable applications for a solid state amplifier, dominated technological advance in amplifiers. Thermionic valves continued to be used in many applications but upon the emergence of the transistor paradigm there was almost a complete cessation of interest in attempts to further develop valve technology.

It is postulated that the emergence of a new paradigm depends initially on the perception by one or a small number of technologists of an exemplar, the development of which suggests not only useful solutions to a wide range of existing technical problems but also the potential of new capabilities. The exemplar may be a recent scientific or technological development or it may be an event known for a long time which, because of changes in economic or social conditions, may become an exemplar of a potentially successful paradigm. It is apparent that in the judgment of a potential exemplar by these criteria, the prediction of a considerable period of successful activity before the exploitation of the paradigm approaches a plateau involves a large element of intuition. It is on this basis, however, that a group of individuals characteristically small in number is attracted to the investigation and exploitation of the new paradigm. It is only as demonstrations of the value of the paradigm in leading to new problems and new solutions accumulate that the larger community of technologists active in the field will perceive the potential of the new paradigm.

*Conclusions*

What then has this discussion contributed to an understanding of technology? It may be obvious, but it apparently needs stating that in order to examine factors affecting the growth of technology it is necessary to have a satisfactory understanding of the mechanism of growth of technology. It is the contention of the author that the view of technology as a system of knowledge, developing within a framework predominantly paradigm-bound, but with occasional paradigm-shifts provides a basis for the development of a model of the internal structure of technology.

The paradigm has clearly been shown to be a useful descriptive term, but, far more importantly, it has considerable explanatory power with respect to the periodic form of technological growth. For the usual external economic, social, or even scientific, factors cannot adequately account for the historically observed process of steady development of a particular approach or set of ideas by minor innovations, with the occasional major dislocation and emergence of an entirely new approach to a particular kind of technical problem.

This view of the internal dynamic of technology obviously could have many widespread implications. Thus technology forecasting has been developed over the last decade into quite a sophisticated series of techniques. However they are all limited by the lack of an adequate model for the progress of technology, as none have considered an internal dynamic. It is suggested that examination of a variety of technological paradigms may lead to the emergence of a number of characteristic features, particularly in regard to lifetime from inception to saturation, and indicators of approaching saturation, which may be of considerable significance to technology forecasting.

An analysis in terms of interacting paradigmatic systems of knowledge, each with its own internal dynamic could also be of considerable value with respect to the nature of the relationship between science and technology. One obvious approach would be to examine the way in which the knowledge of science contributes to the formation and overthrow of the paradigms of technology, and vice versa. Thus the emergence of a new paradigm in technology often sets problems of understanding for scientists to solve within their own paradigms. Some of the products of technological knowledge are incorporated within the paradigms of science as standard instruments for data collection. On the other hand developments within science may, at the appropriate time, lead to a paradigm-shift in technology. Certainly every technological paradigm contains essential elements of scientific knowledge. Such an approach is the basis of a recent study of industrial innovation (Johnston & Gibbons, 1971).

It is apparent from this paper that a complete understanding of the internal structure of technology will not be easily achieved. The author has sought only to outline an important subject of which little is known, and to suggest an approach to its study.

*Manchester University.*

[1] This is characterised by the increasing study of the R. & D. process, from psychologists on individual creativity to organisation theorists on management of R. & D.

[2] Prominent among the critics of the growth of technological monism are Roszak (1969), Dubos (1970), Mumford (1967), and Ellul (1965).

[3] Kuhn's theories have given rise to much controversy, exemplified by the Proceedings of the International Colloquium in the Philosophy of Science in 1965, published as *Criticism and the Growth of Knowledge* (Lakatos and Musgrave, 1970) in which Kuhn is severely criticised by the Popperians; Martins (1972) has questioned the application of a theory based on physics and chemistry to all sciences: Bloor (1971 suggests the Popperian research programme is moving closer to that of Kuhn; Dolby (1971) has adopted Kuhn's relativism to study the sociology of knowledge in natural science; King (1971) discusses Kuhn's theory as the genesis of the sociological study of authority in science.

## *References*

Agassi, J. 'The Confusion between Science and Technology in the Standard Philosophies of Science', *Technology and Culture, 7,* 1966, 348-366.

Bloor, D. 'Two Paradigms for Scientific Knowledge?', *Science Studies, 1,* 1971, 101-115.

Bunge, M. 'Technology as Applied Science', *Technology and Culture, 7,* 1966, 329-347.

Burns, T. 'Models, Images, and Myths' in Marquis, D. G. and Gruber, W. H. (eds.), 1969, 11-23.

Cardwell, D. S. L. 'The Academic Study of the History of Technology', *History of Science, 7,* 1967, 112-124.

Dolby, R. G. A. 'Sociology of Knowledge in Natural Science', *Science Studies, 1,* 1971, 1-21.

Dubos, R. *Reason Awake: Science for Man,* Columbia University Press, New York, 1970.

Ellul, J. *The Technological Society,* Jonathan Cape, London, 1965.

Feyerabend, P. K. 'Consolations for the Specialist', in Lakatos, I., and Musgrave, A. (eds.), 1970, 197-230.