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The Relationship between Technology and Science: Some Historical and Philosophical Reflections.
Part II

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CONSEQUENCES OF THE TAS VIEW

The dominance of the idealist, TAS view as a description of science/ technology relations has influenced the way in which history of science and technology has been written, and this in turn has influenced the story-line presented to students in school and university curricula.

Other factors

One consequence is that it tends to elevate the importance of scientific ideas and downplay the contribution of other factors necessary for developing a technological innovation. This is not a *necessary* consequence of the TAS view, since simplistic explanations of complex phenomena are hardly the exclusive property of idealists. However, a philosophical position which treats formalised knowledge as the most potent source of innovative praxis is likely to ignore the important, even essential part played by other forms of thought and other sources of influence. For example, the technologist may use some problem-solving procedures (e.g. trial-and-error) which do not involve the application of a scientific principle. The motivation for producing the artefact, and the method used to produce it, may be the result of powerful cultural influences.

Trial-and-error methods. Applied science certainly played a central part in the development of the photo-copier: the development of xerography ('dry writing') depended upon making use of the photo-conductive properties of selenium. However, the inventor (Chester Carlson) was beset by a host of problems in turning his creative idea into a workable prototype. One was the problem of finding a material which would wipe the excess powdered ink off the selenium drum after each copy had been made and which could be accurately cut to the right size. The solution – the belly fur of the Australian rabbit – was found by trial-and-error, not applied science (Owen, 1986).

Trial-and-error methods have a distinguished history in technological innovation. They were used by James Watt in his attempt to find strong, durable, tight-fitting and low-friction materials for the piston and cylinder of his steam engine (Scherer, 1965), and by Thomas Edison in his search for suitable materials for his electric light bulb (McCormack, 1985). Vincenti (1990, Ch. 2) concludes his essay on the development of wing design by observing that in the first decades of this century,

> No realistically useful theory existed, and empirical knowledge was meager and uncodified. Design was almost exclusively by simple cut-and-try; that is, by sketching an airfoil and trying it out. No other way was possible (p. 50).

Using trial-and-error, however, is almost the antithesis of applying a scientific principle: it is the technological method one uses when one *lacks* the appropriate scientific knowledge. As Bannock, Baxter & Rees (1978) point out, 'Technology is not merely applied science . . . things are often done without precise knowledge of how and why they are done except that they are effective' (p. 433).

Cultural pressures. Intangible, ideological factors – the cultural forces which support or inhibit a particular line of technological innovation – may be crucial in explaining how and why that innovation developed. Mumford (1961) argues that it is 'impossible to isolate the invention from the inventor, or the inventor from the place and the labor force and the culture that presented him with his opportunities and his incentives – or placed obstacles in his way and rejected his results' (p. 236). He offers a diverse set of historical illustrations: the building of the Egyptian pyramids, the mechanical devices of the Benedictine monks, and the evolution of some modern artefacts from children's toys.

The pyramids, Mumford argues, were built not by innovative mechanical devices, but as a result of the religious power invested in the Pharaoh to command 'the first complex machine, the thousand-legged human machine, made of specialized, inter-changeable, and replaceable parts, operating from a single control center . . .' (p. 232) The means to do this 'did not come from the internal development of technics: just the other way round, it was the magnification and exaltation of human power that came in with the new solar religions, opening up immense vistas in time and space, that made possible the contrivance of an altogether new species of complex machine' (p. 233).

The Benedictine monks' desire for a well-ordered life which regarded work as a moral obligation but which demanded time for religious devotion led to the invention of mechanical clocks and labour-saving devices. Slide- and movie- projectors and helicopters, Mumford notes, originated from 19th-century mechanical toys for children, a genre of artefacts that began to be developed in the late Middle Ages as a result of increased attention to child care. The story of the Pyramids has modern parallels: the production of the atomic bomb and development of the space program also depended upon the power of a state authority to direct the behaviour of thousands of personnel.

Mumford's point about obstacles and rejection is also significant. Chester Carlson's development of the photo-copier was almost scuttled by a serious shortage of finance; even when the first working model had been built, IBM accepted advice from consultants that the market for such machines was likely to be small, and declined to become involved (Owen, 1986). Two centuries earlier, James Watt experienced financial difficulties during his attempt to turn his model steam engine into a successful commercial machine (Scherer, 1965).

Vincenti's discussion of the role of social influences on aircraft wing design applies equally well to other fields. He argues that

> design does not take place for its own sake and in isolation. Artifactual design is a social activity directed at a practical set of goals intended to serve human beings in some direct way. As such, it is intimately bound up with economic, military, social, personal and environmental needs and constraints (1990, p. 11).

The role of instrumentation

A second consequence of the TAS view is that it tends to de-emphasise the crucial role of instrumentation in promoting science. Again, this is not a *necessary* consequence – anyone is free to investigate the role of instrumentation, regardless of their philosophical position on the technology-science relationship – but it is not too difficult to see how a view which gives primacy to the part played by scientists' *ideas* might tend to treat the hardware as 'transparent', of secondary importance.

Earlier, we noted Buchanan's argument that Greek science arose from an analysis of the nature of the useful arts, and explored Ihde's ontological position that our scientific views of the world are shaped by our technological instrumentation. Ihde (1979) notes that the experimental nature of contemporary science is commonly regarded as the characteristic which distinguishes it from classical science, but comments that

> it is not so much the experiment which distinguishes contemporary from classical science as its technological embodiment. Whereas classical science was limited for the most part to speculation, theory, deductive cleverness and primitive measurements, none of which are absent from contemporary science, the technological instrumentation now available allows inquiry to be extended in ways never dreamed by the ancients (p. 36).

Technology thus becomes a necessary condition for science, in its modern sense of knowledge based upon experiment and measurement. Ihde argues that modern science is 'necessarily embodied in its instrumentation' (1983a, p. 235). Greek science, in contrast, remained largely speculative, since it lacked the instrumentation to investigate its theories.

It is of course easy to find numerous examples of instruments being used to extend scientific knowledge. Galileo's use of the telescope to investigate Jupiter and the moon demonstrates the contribution of optical technology to astronomy; accurate beam balances for weighing chemical reactants and products were essential to the development of modern chemistry; Captain Cook's navigational and scientific achievements in the 18th century were made possible only through the prior development of chronometers which permitted the precise measurement of longitude. In all of these examples, instrumentation provided the means of sharpening the senses, of providing more accurate measures than could be obtained by the unaided hand and eye. Ihde would describe these as examples of directly mediated embodiments, instruments akin to the dentist's probe or microscope which keep the observer in direct touch with the world, simultaneously amplifying the power of observation and reducing the field of vision.

Modern instrumentation goes well beyond this, generating data about entities which are totally unobservable to the senses. Scientific fields such as nuclear magnetic resonance or radio-astronomy are based entirely on studies of the output of electronic and electro- magnetic inscription devices which form part of the instrumentation. For Ihde, such devices involve the 'mediated mediation of hermeneutics'; a spectrographic photograph of a star, for instance, can be regarded as a type of 'text' which must be 'read' by someone 'literate' in the language (1979, pp. 35–36). For Ihde and other writers in this genre – see for example Latour & Woolgar (1979) for a detailed analysis of the role of interpretation in translating the output of inscription devices in a biochemical research institute into scientific knowledge – instruments and human interactions with them move into the foreground.

Some scientists have publicly acknowledged their debt to technology, and the instruments it provides. Henry Power (1623–1668) was a physician and member of the Royal Society who made microscopic observations of insects and conducted experiments on magnetism and atmospheric pressure. In the Preface to his book, *Experimental Philosophy* (1664), he wrote:

> How much therefore are we oblig'd to modern Industry, that of late hath discover'd this advantageous Artifice of Glasses, and furnish'd our necessities with such artificial Eys that now neither the fineness of the Body, not the smalness of the parts, nor the subtilty of its motion, can secure them from our Discovery? (quoted in Vickers, 1987, p. 88).

Power expressed the hope that the unlimited potential of 'Mechanical Industry' (i.e. technological inventiveness) would some day allow 'Magnetical Effluviums', 'Solary Atoms of Light' and 'springy particles of Air' to be observed directly. And, he went on, 'this I am sure of, That without some such Mechanical assistance our best Philosophers will but prove empty Conjecturalists, and their profoundest Speculations herein but gloss'd outside [i.e. deceiving] Fallacies' (p. 89).

Initiating new lines of scientific enquiry

A third consequence does follow fairly naturally from the TAS view. If one adopts the line that technology is applied science, one will be less inclined to look for cases illustrating the reverse, of technology generating new science. Yet this does occur: the role of technology in science is not limited to its contribution to instrumentation. Technology results in new concepts and questions for scientific research. Available artefacts provide conceptual models for scientists to use: it is doubtful whether William Harvey could have developed his ideas about the circulation of the blood if pumps had never been invented. After the Industrial Revolution, some technologists began to make scientific contributions to their own fields; for example, James Francis, a 19th century American technologist, not only improved the efficiency of water wheels by adopting experimental procedures and mathematical analysis, but also contributed to scientific theory in the process (E. Layton, 1981). Similarly, Carnot's studies of the efficiency of heat engines laid the basis for developments in the physics of thermodynamics.

New technology, especially during the past century, began to draw attention to fresh areas for scientific investigation. Marconi's transmission of trans-Atlantic radio signals led to the discovery of the Heaviside layer of the ionosphere. Attempts to improve the design of electric motors through measurement of electrical quantities and mathematical analysis stimulated work on differential equations. Engineers' studies of the elasticity of materials provoked physicists into thinking about the possibility that the 'ether' was an elastic medium which transmitted light.

Major scientific discoveries were made through research conducted with technological motives. Feibleman (1961) notes that many modern advances in pure science have come from industrial laboratories: 'from the Bell Telephone laboratories alone have come the discoveries by Davisson and Germer of the diffraction of electrons, by Jansky of radio astronomy, and by Shannon of information theory' (p. 314). Sometimes the research outcomes are quite unintended: Morison (1974) describes how research conducted in the General Electric laboratories in an attempt to improve the design of the light bulb led Irving Langmuir to study the mechanisms of chemical reactions at surfaces, work which won him the Nobel Prize for Chemistry in 1932.

An idealist reading of history

Ihde (1983a) has pointed out that one of the consequences of the idealist (i.e. the TAS) view is that it leads to an interpretation of the history of modern science and technology in which the dominant events, in chronological order, are the revival of the Greek scientific spirit leading to the Renaissance, the discoveries of Galileo, Kepler, Copernicus and Newton, the development of mathematics, the decline in the power of religion to explain cosmology, the advent of the Industrial Revolution and the rise of modern 'high technology' as outcomes of scientific theory. Ihde observes that those who wish to maintain this idealist position then have to make a distinction between 'modern', 'scientific', 'high' technologies (e.g. computers) and traditional, 'low' technologies (e.g. waterwheels). This distinction becomes necessary, since 'all people and societies use and have technologies whether or not they have science in our sense' (p. 238). As we have seen earlier, Ihde has argued that such a distinction is unnecessary; Renaissance science owes as much to well-developed medieval technology as it does to any revival of Greek science.

A revolutionary reading of technological innovation

Another consequence of the TAS view arises when it is combined with a revolutionary view of scientific change. Basalla (1988) points out that recent scholarship in the history and philosophy of science has tended to view scientific change as discontinuous, as a series of *revolutions*, 'a political metaphor that implies a violent break with the past and the establishment of a new order' (p. 26). If this view is coupled with a belief that technology is simply applied science, then it naturally follows that 'technological change too must be discontinuous' (p. 27). (In this reading of the history of technology, the inventor tends to be accorded heroic status, a person who conceives a brilliant new artefact out of nothing.) Some historians of technology have adopted this view. Basalla cites the work of Edward Constant II, whose account of the history of the turbojet aircraft engine treats it as a revolutionary advance which had little in common with earlier piston-driven engines.

Basalla however rejects the proposition that technological innovation is revolutionary. He likens the diversity of artefacts in the made world to the diversity of life forms in the natural world, and deliberately employs this metaphor to argue for a continuous, evolutionary model of technological development. He contends that 'Novel artifacts can only arise from antecedent artifacts . . . new kinds of made things are never pure creations of theory, ingenuity or fancy' (pp. vii–viii). He discusses various innovations – simple artefacts such as barbed wire and complex ones such as Edison's electrical supply system – and shows that their novel features can always be linked to something which existed earlier. In the case of the turbojet engine, he points out that the design drew upon a

> two-hundred-year-old tradition of turbine development that encompasses water turbines, turbine water pumps, steam turbines, internal combustion gas turbines, piston engine superchargers and turbosuperchargers. None of these has pistons and cylinders but they all have a turbine wheel with fins or buckets that, when acted upon by water, steam or hot gases, cause the wheel to rotate rapidly (p. 29).

Basalla argues that novelty can be introduced in the midst of continuity from various sources: 'the human imagination, socioeconomic and cultural forces, the diffusion of technology, and the advancement of science' (p. viii). A society can exploit only a small fraction of all possible novelties, and a selection must therefore be made, usually in accordance with the values of that society and its perceived needs.

THE COMPLEXITY OF APPLICATION

Superficial consideration of 'application'

The TAS position is not of course universally *untrue*. Technologists will use whatever knowledge and skills they have to hand in order to confront a technological problem, and there are many cases (especially in modern times) of scientific knowledge providing a necessary foundation for technological innovation. However, even in cases where an innovation clearly does follow a relevant scientific discovery, the TAS view treats the issue of *application* superficially, as if there were an obvious connection between the scientific principle and its embodiment in an artefact. Yet again, this is not a necessary consequence of holding a TAS view; advocates of the view that technology was applied science might simply argue that insufficient research had been done on this aspect of the process. The critic might perhaps reply that an over-weening belief in the power of scientific ideas might prevent the advocate of the TAS view from recognising the difficulties involved in translating ideas into action.

A century ago, Henry Rowland (1848–1901), who trained as an engineer and later became a professor of physics at Johns Hopkins University, seemed to believe in the obvious nature of application:

> It is not an uncommon thing especially in American newspapers, to have the applications of science confounded with pure science; and some obscure American who steals the ideas of some great mind of the past, and enriches himself by the application of the same to domestic uses, is often lauded above the originator of the ideas, who might have worked out hundreds of such applications, had his mind possessed the necessary element of vulgarity (quoted by Finch, 1961, p. 326).

The epistemological belief implicit in this extraordinary statement is that it is simple to turn a scientific idea into a technological application. (In passing, we might note that the statement ignores the obvious point that scientists are expected to publish their findings, so that the use of their ideas by others can hardly be called 'stealing'!)

Application as algorithm

One immediate problem in this discussion is that 'application', like many other abstractions in the English language, has a wide range of connotations. In scientific and mathematical contexts, it is often used to refer to the process of using an algorithm ($[a + b]^2 = a^2 + 2ab + b^2$) or a scientific law statement (Ohm's law) to deduce a correct answer to a well-defined question. Thomas Edison's request to his applied physicist, F. Upton, to calculate the amount of copper needed to implement his electric street-lighting proposal (Agassi, 1966) exemplifies this meaning of 'application'. If one knows the relevant formula or law, it is a straightforward matter to use it to obtain a correct answer. Rowland's position reflects this connotation of 'application'.

Application as selection

Actually, the connections between the ideas that form part of a body of scientific knowledge and their embodiment in a practical outcome are seldom self-evident. The technologist wishing to apply scientific knowledge to the solution of a technological problem must often first decide which knowledge is appropriate. Bunge (1966, p. 333) notes that artefact construction frequently does not require the application of all the scientific knowledge available in the field at any given time. Most modern optical instruments, for example, can be adequately designed with a knowledge of 16th century ray optics; wave theory can be drawn upon to explain, in outline but not in detail, other effects – mostly undesirable – such as chromatic aberration. Wave equation descriptions of events such as the movement of a camera shutter are of purely academic interest, of no concern to the camera designer.

Thus judgements have to be made about what knowledge to select, and the links between scientific knowledge and practical action may therefore be quite tenuous. Bunge points out that a scientific theory can be regarded as true but technologically irrelevant: quantum theory, for example, is useless for explaining car collisions. The converse is not true: the success or failure of an artefact provides no index of the truth value of the theory on which it is supposedly based. In some cultures, magical exorcisms were combined with craft knowledge to make excellent steel swords.

Application involves adopting differing criteria

The difficulty of applying scientific knowledge to practical outcomes is exacerbated by the very form of that knowledge. Science is concerned with precisely defined variables, with knowledge of relationships obtained under controlled conditions. In real situations, however,

> the relevant variables are seldom adequately known and precisely controlled. Real situations are much too complex for this, and effective action is much too strongly urged to permit a detailed study – a study that would begin by isolating variables and tying some of them into a theoretical model (Bunge, 1966, p. 335).

Scientific demands for precision are sometimes unnecessary in technology. Artefacts can often be successfully designed and made without (or even despite) scientific precision, because the 'accuracy requirements in applied science and practice are far below those prevailing in pure research so that a rough and simple theory supplying quick correct estimates of orders of magnitude very often will suffice in practice' (p. 334).

Application involves translating and reshaping knowledge

Before a technologist can make use of a scientific idea, that idea must often be translated into a more useable form. This can be an exceedingly complex process, and may include any of the following:

* translation from one language to another;
* translation from 'physicists' language' to 'engineers' language';
* supplementation of documented knowledge with tacit knowledge derived from personal experience;
* translation from the inventor's idea through to design, prototype and final manufactured product; frequently, additional technical problems have to be surmounted along the way.

Scientists and technologists may use different forms of language in describing their work; successful application may first require someone to act as an interpreter. (Sometimes, this is literally true: some of the early mathematical treatises on the ideal shape of gear wheels were written in Latin, totally unintelligible to the average millwright!) Feibleman (1961) notes that modern theories, especially in physics, are

> of such a degree of mathematical abstraction that an intermediate type of interest and activity is now required. The theories which are discovered in the physicists' laboratories and published as journal articles take some time to make their way into engineering handbooks and contract practices. Some intermediate theory is necessary for getting from theory to practice (p. 309).

Even when scientists deliberately set out to help technologists solve practical problems, the form of communication may inhibit effective application. James Clerk Maxwell, for example, did pioneering work on electromagnetic theory; he also did some important work on the analysis of stresses in frameworks and attempted to solve practical problems. However, his publications in both fields first had to be 'translated' before they could be used by engineers. Translation often involves 'extensive reformulation and an act of creative insight' (E. Layton, 1971, pp. 577–578).

The development of the direct-current dynamo during the 19th century provides another illustration. Henry Rowland, mentioned earlier, pursued 'pure' research and published some important work on magnetic permeability and the mathematics of electromagnetic circuits. He failed to make practical use of his findings, although they were relevant to improving the design of the d.c. dynamo; he seemed to be more interested in discovering laws of nature than industrial design principles. Meanwhile, a practising engineer in England, John Hopkinson, working in co-operation with Thomas Edison, had devised a graphical method of describing dynamo behaviour which allowed major improvements to be made, by changing the dimensions of some of its parts (Mayr, 1971; E. Layton, 1971). (There is some delightful irony here in the light of Rowland's disparaging remarks about the vulgarity of inventors who 'stole' the ideas of pure scientists!)

The re-shaping of scientific knowledge for technological purposes often requires additional skills (e.g. engineering skills) which are not deducible from the scientific knowledge being applied, a point already recognised in 1922 by J. D. North, a British aeronautical engineer, in a paper given to the Royal Aeronautical Society:

> Aeroplanes are not designed by science, but by art in spite of some pretence and humbug to the contrary. I do not mean to suggest for one moment that engineering can do without science, on the contrary it stands on scientific foundations, but there is a big gap between scientific research and the engineering product which has to be bridged by the art of the engineer (cited by Vincenti, 1990, p. 4).

Vincenti goes on to comment that it is the creative and constructive knowledge of the engineer which is needed to implement that art; technological knowledge 'in this view appears enormously richer and more interesting than it does as applied science' (p. 4).

Translation of knowledge into artefact may be difficult because the scientific knowledge was gained under idealised or laboratory-scale conditions; applying it to real-life, full-scale conditions may first require the surmounting of additional problems. For example, A. R. Hall (1961) notes that the 17th century Danish astronomer Ole Roemer and members of the French Academy of Sciences had worked out that gear teeth would mesh more accurately if they had epicycloidal profiles, but this was of no practical value to millwrights (even had they known of the research), since they lacked the machinery for cutting suitable material. Wood could have been cut to shape, but was unsuitable for gear teeth, while iron was impossibly difficult to work except on a small scale.

The story of the extraction of aluminium provides a second illustration of this point. Hans Christian Oersted first obtained traces of impure aluminium in 1825 by mixing potassium-mercury amalgam with anhydrous aluminium chloride; two years later, Friedrich Wöhler tried a similar reaction, using potassium in place of the amalgam. By 1854, H. St. Claire Deville had made some aluminium leaf electrolytically. However, practical exploitation of this knowledge by Charles H. Hall in the United States and (independently) P.L.C. Héroult in Switzerland took another thirty years, and large-scale commercial exploitation another twenty years. Viability depended upon the development of other technologies, namely the Bayer process for concentrating the aluminium oxide used as the raw material, and the electric furnace and the dynamo for producing high temperatures and currents. The first commercial production, through the electrolysis of aluminium oxide dissolved in molten sodium-aluminium fluoride, was carried out in Pittsburgh in 1888, but the yield was small, limited to about 20 kg per day. Mass production was not possible until cheap hydroelectric power became available in the early 1900s (Rae, 1960; Bronowski, Barry, Fisher and Huxley, 1963, p. 118; M. B. Hall, 1976).

The basic technology of the jet engine was known to Hero of Alexandria in the 1st century, when he used a jet of steam in his toy 'aelopile'. Rockets have been in use for military and other purposes since the 13th century. The basic physics – Newton's action-reaction law – was elucidated in the 17th century, and the specific idea of a gas-driven turbine was put forward late in the 18th century. However, when, in 1929, a 22-year old RAF cadet named Frank Whittle conceived of applying the gas turbine to jet propulsion,

> he still had a dozen years of frustrating effort ahead of him before he had an engine operating in actual flight. His difficulties were not matters of fundamental principle, but technical points like the proper setting of turbine blades or the control of air turbulence in the compressor (Rae, 1961, p. 397).

Smith (1961) observes that metallurgists must always go beyond scientific knowledge and adapt materials to all kinds of conditions, including those imposed by economics and politics. He notes that

> chemical theory is not enough. A knowledge of complex properties of materials is as important as of the kinetics of reactions. In the development of the great majority of processes, the greatest task is the finding of materials of construction which will be compatible under the conditions encountered. Fundamental science cannot yet eliminate trial of refractories or effectively balance the economics of supplies of various sources of materials differing in impurity content (p. 365).

The translation of the idea of photo-conductivity into the design of the photo-copier provides a more recent illustration of the practical problems involved in turning a scientific idea into a working artefact. The science of photo-conductivity was based on studies of sulphur, and Carlson's early experiments were made using this element. However, sulphur is not a very durable material for use in a machine. Finding a better substitute (selenium) and designing a precisely-made system embodying the idea, took years of work.

Scientific knowledge is public knowledge, propositional knowledge, knowledge that can be shared within and beyond the scientific community through oral and printed forms of communication. Although technological knowledge can also be shared, through blueprints, technical handbooks and technical papers, such documents may be insufficient to allow scientific ideas to be translated into technological applications. Basalla (1988, pp. 83–86) observes that *all* of technology can never be translated into words, pictures or mathematical equations; there is always a place for the practitioner with tacit knowledge, gained through personally acquired craft skills or through close observation of others with those skills if an idea is to be translated into an artefact. (Tacit knowledge is also needed by scientists to get their experiments to 'work'.) Basalla tells the story of how an American invention – the transistor – laid the basis for the emergence of the giant Japanese electronics industry. In the late 1940s, a group of young Japanese engineers banded together to form the Tokyo Telecommunications Engineering Company. Masaru Ibuka, one of the group, heard about the transistor in 1953 and bought the patent licence the following year. Ibuka sent technicians to the US to collect all the available technical information on the invention. The technicians also 'visited laboratories to observe transistors being made, and also talked to the scientists, engineers, and technicians working on all aspects of transistor production'. This knowledge was essential for developing the first Japanese pocket radio receiver in 1955. In the same year, the company changed its name: to Sony.

Finally, the process of moving from invention through to prototype and commercial product is often very complex, requiring skills not necessarily possessed by the scientist or inventor. Rabi (1965) was a distinguished US physicist involved in developing microwave radar during the second world war, and was close to people engaged in other major projects (the atomic bomb, the transistor, the maser and the klystron tube). He argues that the process of translating a scientific idea into a technological product involves many diverse steps, each usually requiring people with highly specialised abilities. The ability to conceive of an invention, he argues, is very different to the ability to see through the numerous details of the process of making it. Before the magnetron tube could be manufactured, several men spent months finding out 'how to describe it, to reduce it to drawings, so that it could be properly made by the manufacturers' (p. 12). A prototype could then be constructed in the model shop; the next task 'was to break down the stages of production into simple procedures so that the magnetron could be made economically and in such a way that each one would work the way it was supposed to' (p. 13). Rabi likens the harmonious co-ordination of this process to the conducting of a symphony orchestra.

Rae (1961), in his essay on the history of aviation, offers a statement consistent with the arguments in this section:

> There have been long periods in history when science and engineering developed pretty much independently of each other; this indeed was the usual situation until just before the Industrial Revolution. Conditions have changed considerably since, but it is still possible for a historian to defend the validity of these two propositions: one, that for technological advance it is not necessary that the whole body of underlying scientific theory and information be known; two, that even if the theory and data are complete (an ideal state not yet encountered in experience), it does not follow that they can forthwith be put to practical use (pp. 391–392).

TECHNOLOGY AND SCIENCE: RETHINKING THE RELATIONSHIP

If we reject the TAS position as historically unsound and simplistic, with what should we replace it? An answer to this question could proceed along three lines:

- technology and science, although increasingly related in modern times, are autonomous fields with their own distinctive ways of working;
- technology, although not synonymous with applied science, has evolved (particularly during the past two centuries) by adopting scientific approaches to the solution of its own problems;
- technology and science represent interacting communities of people who learn from each other but who hold to differing sets of values.

Autonomous and distinctive fields

Instead of considering technology as applied science, it may be more defensible to regard the two fields as autonomous and distinctive. George Wise, an historian of technology, has argued that 'treating science and technology as separate spheres of knowledge, both man-made, appears to fit the historical record better than treating science as revealed knowledge and technology as a collection of artifacts once constructed by trial and error but now constructed by applying science' (quoted by Vincenti, 1990, p. 4).

The argument that technology and science involve differing forms of knowledge requires some elaboration. Science, it might be argued, encompasses an extremely wide range of fields, from astronomy through to zoology, each with its distinctive domain of subject matter, substantive structure (networks of concepts and principles) and syntactical structure (modes of reasoning) (Gardner, 1975). Why not regard technology as simply one more entry in the list of sciences, the science of designing and making artefacts?

The reason for not doing so is that technology is distinctive: the motivations for increasing technological knowledge and the modes through which that knowledge is gained are different from the motivations and modes of science. One distinctive motive for seeking new technological knowledge is initiated by cases of *functional failure*. An artefact may fail to operate as intended, sometimes with disastrous and tragic results. The famous Tacoma Narrows bridge collapse of 1940, when engineers failed to consider the possibility that winds could cause resonance in the thin roadway, is a classic example. Sometimes an artefact designed for use under one set of conditions fails when subjected to a different set. Thus, a hand-pump designed to work satisfactorily for years on a single-family farm may break down quickly when used by hundreds of people daily in a Third World village; a wing design entirely adequate for sub-sonic flight may fail when used in aircraft flying at near-sonic or supersonic speeds. The concept of functional failure is simply not part of the substantive structure of any of the sciences. Petroski (1985) has written a whole book on the contributions made by engineering failures to the improvement of design.

Functional failure, however, is not the only motivation. Vincenti (1990) refers to Edward Constant's notion of *presumptive anomaly*, which occurs 'not when the conventional system fails in any absolute or objective sense, but when assumptions derived from science indicate either that under some future conditions the conventional system will fail (or function badly) or that a radically different system will do a better job' (p. 47). Vincenti cites research on airfoil designs which would extend laminar flow over the wing (i.e. delay the onset of turbulent flow) in order to reduce friction drag as an example of this type of motivation. It was not that existing wing designs were failing; rather, there was a perception that radical changes might do a better job.

Both of these motivations arise from a desire to improve the performance of an artefact, either actually or hypothetically. A third source of motivation reflects, not so much a desire for better performance, but a desire to control that performance. If a product is sold with guarantees that it will operate at a certain level of performance, the manufacturer may wish to increase certainty by seeking additional knowledge about the factors determining that level of performance.

Technology also employs distinctive approaches to the gaining of new knowledge. In the final chapter of his book on the epistemology of aeronautical engineering, Vincenti (1990) develops a *variation-selection* model, based on the work of Donald Campbell, to describe the growth of technological knowledge. The variations are design changes, often made blindly. 'Blind' does not mean random or unpremeditated; it means that the outcome cannot be foreseen on the basis of current knowledge. Some of the early aeroplane designs, which had horizontal 'tail' surfaces at the front of the plane and propellers pushing at the back, exemplify such blind variations. Such variations are followed by genuine or vicarious trials in which selection – a technological analogue to biological survival of the fittest – takes place. Such approaches to gaining knowledge appear to have no counterparts in scientific research.

David Layton (1990), citing Staudenmaier (1985), argues that technological knowledge is not

> the same in form, and sometimes in substance, as the knowledge generated by the basic sciences. It is structured by the tension between the demands of functional design, on the one hand (that is, it must enable the achievement of some design purpose), and the specific constraints of the ambience, on the other (that is, the contextual constraints such as cost-limits, deadlines, ergonomic and durability requirements, individual and social preferences). Because of these differences those engaged on technological tasks have often to rework scientific knowledge in order to be able to use it (p. 13).

The transformation of technology

During the past two centuries, technology has become an applied science in a sense which is rather different to that implied by the TAS view. Technology has drawn upon science by adopting its social institutions and research methods. Until the 17th century, technical improvements were largely the fruits of ingenious craftsmanship rather than the consequence of a superior intellectual system. A. R. Hall (1963) argues that this began to change as philosophers began to argue for the importance of obtaining more certain knowledge by adopting experimental and mathematical procedures:

> Bacon's proclamation of the technological utility of science was echoed through his century and reflected in attempts to solve the problem of determining longitude at sea, programs for agricultural reform, a very few attempts to apply mathematical analysis to machines, endeavors to treat problems of river control and land drainage scientifically, interest in the art of war (especially ballistics), and above all in the continued effort to perfect medicine through chemical and biological investigations (pp. 128–129).

McGee (1989) observes that the debate about the relationship between technology and science

> revolves around the direction of the flow of information between communities of science and technology. But these communities have come to share more than knowledge. Since the beginning of the nineteenth century the technological community has borrowed heavily from the methods and organisation of science. In the process, technology has become scientific (p. 29).

The largely independent pathways of technology and science began to intertwine in the 18th century; after the Industrial Revolution, instances of technological innovations arising from scientific discoveries became more numerous. Discussion of the change in the nature of technological development requires a distinction to be made between the use made by technologists of ideas derived from science and their use of scientific modes of enquiry to investigate the behaviour of machinery in ways that permitted technological advancement. Edwin Layton, citing the work of Koyré (1948), argues that science began to influence technology, not directly, through its laws and findings, but subtly, indirectly, through cultural influence, through the transformation of technology's own system of thought:

> In a specific case, the idea of a world governed by precise mathematical laws was transmitted to technology through Galileo's and Huygens' conversion of the mechanical clock into an instrument of precision. The idea that the universe is governed by precise mathematical laws, it should be noted, was not a scientific result, but one of its presuppositions (E. Layton, 1974, p. 36).

The major changes in the technology-science relationship were not simply the result of technologists making increased use of scientific knowledge. Rather, the nature of technological development itself began to change, as technologists began to adopt scientific modes of research – experimental investigation and mathematical analysis – to investigate technological problems. Technology, formerly a craft, became a profession, replete with laboratories, research journals and professional societies (E. Layton, 1977). Technologists and scientists began to engage in a two-way relationship, culminating in the 20th century in the formation of inter-disciplinary teams.

The adoption of scientific methods by technologists can be illustrated if we examine attempts to improve the efficiency of the waterwheel, an important source of power in pre-Industrial Revolution times. As Cardwell (1965) has observed, 'Classical mechanics, although admirably adapted to solving such problems of accelerated motion as the behavior of planets and satellites, did not lend itself readily to the study of the power obtainable from unaccelerated machines' (p. 192). In 1704, Antoine Parent proposed a relationship between the speed of water and the power of a waterwheel. It turned out to be incorrect, but it represented the beginnings of a new approach to technological progress: the scientific study of machine behaviour, using mathematical methods and experimental trials. In the middle of the century, the British engineer John Smeaton conducted experiments to investigate the behaviour of waterwheels under various conditions. Technologists using such approaches were able to demonstrate that overshot waterwheels were more efficient than undershot waterwheels, and that curved wheel blades were more efficient than straight ones. The relationships between water speed and 'useful effect' (power) found as a result of Smeaton's research were not laws of nature; rather,

> they were lawlike statements about man-made devices. They were not logical deductions from the science of mechanics; they constituted the germ of a new technological science (E. Layton, 1971, p. 566).

Layton went on to note that such writings laid the foundation for the enormous changes in the nature of engineering during the 19th century. Some branches of engineering, such as strength of materials and hydraulics, built directly upon science; others, such as the kinematics of mechanisms, evolved from engineering practice. In both cases, engineers adopted the theoretical and experimental methods of science and employed mathematical theory. In the process, the approaches adopted by engineers and scientists to fields such as the strength of materials began to diverge, engineers being more concerned with directly measurable entities useful for design purposes and scientists being more interested in fundamental entities such as atoms.

Treating the machine as an object of scientific study was central to the development of electrical engineering. Kline (1987) notes how the successful development of the alternating-current induction motor required electrical engineers to go beyond Maxwell's electromagnetic theory and develop an engineering theory *of the motor* in order to make progress.

Drucker (1961) offers a different interpretation of the change in the science-technology relationship. He doubts whether the explosive change in the human condition during the past two centuries should be attributed to the progress of science, and proposes instead that the principal factor was a fundamental change in the concept of technology. Old technologies (agriculture, engineering, medicine) became systematic public disciplines. This brought about revolutions in these fields, but the change

> owed little or nothing to the new knowledge of contemporary science. In fact, in every technology the practice with its rules of thumb, was far ahead of science. Technology therefore became the spur to science; it took, for instance, 75 years until Clausius and Kelvin could give a scientific formulation to the thermodynamic behavior of Watt's steam engine. Science could indeed have had no impact on the Technological Revolution until the transformation from craft to technological discipline had first been completed (p. 342).

Drucker goes on to argue that science was itself transformed by the emergence of systematic technology. Science's definition and image of itself changed; although scientists would still maintain that their goal was the systematic search for rational knowledge, the term 'knowledge' shifted in meaning from 'understanding' i.e. focussed on the mind, to 'control' i.e. focussed on application. Drucker's thesis therefore turns the conventional view of technology as applied science on its head: science has evolved into applied science as a result of technology. This resembles Ihde's thesis that science is a tool, arising from technological praxis, which promotes the further development of technology.

A two-way process

One of the consequences of the transformation of technology is that science and technology have developed a two-way relationship; several examples were given earlier. Bernal (1965) considers that while technology could make 'steady and cumulative improvements', notable improvements required scientific advances; at the same time technological successes and difficulties furnished 'a continually renewed field of opportunity and problems for science' (Vol 1, p. 42). For Edwin Layton (1971), the relationship has become symmetrical:

> That is, information can be transferred in either direction. The flow of technology into science in the form of instrumentation has long been recognized; but the traditional model does not provide for the possibility that technological theory might influence science (p. 578).

An illustration of the interweaving of technological and scientific advances can be seen in the story of the development of the first jet aircraft. Rae (1961) notes that the jet engine made it possible to consider flight at near-sonic and super-sonic speeds, but this required radical changes in wing design, air-frame shape and control systems. Changes in one part of the design frequently generated fresh problems which had to be explored in wind-tunnel tests and flight trials. J. H. Kindelberger of North American Aviation observed that, 'As is always the case, the problems seem relatively simple when the solutions have been found, but in the frantic period of exploration it often appears that the laws of physics are capriciously defying our best efforts' (quoted by Rae, 1961, p. 397). The laws of physics are not, of course, capricious: it is simply that generalisations about streamline flow at sub-sonic speeds are inapplicable near the speed of sound. Nevertheless, technological advances were made; the scientific understanding followed.

Alternative models of the technology-science relationship

With the growth of critical attacks on the TAS view and the linear model (science generates technology generates effects) in which it is embedded, scholars began to propose alternative models and theories of the science/technology relationship. Brooks (1965) argued that the conventional analogy of the relationship is that of 'the seed and the plant, basic science being the seed and technology the plant'. However, the occasional cases of technology arising from science are exceptional rather than typical and the seed-plant analogy is misleading. There is a 'multiplicity of connections between science and its applications'; a better analogy might be

> the analogy between the seed and the fertile field. The role of science in the development of technology is to provide the environment in which technological ideas can be exploited, rather than in fact being itself the origin of technological ideas (p. 38).

Basalla (1988) recognises that in the 20th century, science has come to play a much larger role in technological development. However, he argues that

> Proponents of scientific research have exaggerated the importance of science by claiming it to be the root of virtually all major technological change. A more realistic and historically accurate assessment of the influence of science on technological change is that it is one of several, interacting sources of novelty (pp. 91–92).

Kranzberg (1979) observes that scholars have 'done away with the old maxim that technology is simply applied science and that the process of invention is a simple linear progression from basic research to application' (p. xix). However, although several writers, himself included, have attempted to develop models which describe the relationship between science and technology in innovation, he notes that 'nobody has come up with one overall model encompassing all the parameters of science-technology relationships or the even more complex elements involved in innovation. It now appears that innovation most nearly resembles an ecological process and requires a dynamic systems model' (p. xx).

Technology and science: Changing social relations

One reason why the technology-science relation can be regarded as complex and difficult to summarise in the form of a model can be discerned in some of Kranzberg's earlier writings. He reminds us that technology 'does not exist in a vacuum; it develops in a social context, as do all other human activities' (Kranzberg, 1963, p. 139). To conceive of 'science' and 'technology' in abstract terms as bodies of knowledge is to ignore the fact that these bodies of knowledge are developed, maintained and transmitted by *people*. Thus the link between science and technology is affected by the nature of the social relationships among and between groups of scientists and technologists. These relationships, in turn, are dependent upon the relative esteem in which science and technology are held in a society. In many cultures at widely differing times, pure science has been seen as a superior form of activity to technology. The story of the changing relationship between science and technology is also a story of changing patterns of social interactions, from essentially separate groups of philosophers and artisans, to modern, interdependent communities.

The story is a long one, spanning 2500 years; many cultural attitudes still held today can be traced back to ancient Greece. Plato laid the groundwork when he distinguished between the mind and the hand; for Plato, 'formulations of the mind were considered superior to the products of the hand' (Kranzberg, 1963, p. 135). Aristotle, in his *Nicomachean Ethics* (Book I, Chapters 1–2) developed a variant of this theme, arguing that science was pursued for its own sake, while *techné* – art or skill based on knowledge – was a means to an end, knowledge whose purpose was to improve human comfort or survival. For Aristotle, knowledge which was an end in itself, e.g. scientific knowledge or philosophy, was to be valued over knowledge which was a means to an end. Ihde (1979) comments that 'the implicit knowledge in *techné* was praised, but downgraded by the Greeks' (p. xix). Science and technology tended to be developed and maintained by separate social groups, a situation that changed little until modern times. Buchanan (1963), in a discussion of the arts – a broad term encompassing the useful arts as well as the fine arts – notes that practitioners organised themselves

> into crafts and guilds of artisans and technicians. They pass on the skills to their apprentices, they improve the arts, and they tend to have trade secrets. They also tend to generate and maintain theories that add understanding to skill (p. 154).

The separation of social groups, and the Platonic/Aristotelian attitude of superiority of mental over physical work, were also present in Roman times. Gilfillan (1962) in an essay on the slowness of invention in that society notes that:

> A social gap, of uninterest if not contempt, separated the artisan class, in whose hands lay invention and the only knowledge of its needs and problems, from the aristocracy, who possessed the education, science, brains, wealth, and political influence which were also needed for making inventions and putting them into effect. . . . We can find the same prejudice today in various countries . . . (p. 85).

Note the enshrining of a normative position – mind is better than hand – into a social system: upper class minds and lower class hands. This cultural attitude was reproduced in medieval England and Europe. Benne & Birnbaum (1978) note that practical skills were possessed by skilled artisans – metalworkers, silversmiths, farmers, navigators – who passed on their skills directly through master/ apprentice relationships. Science, where it existed at all, was maintained in monasteries, in royal courts, in the early universities and (later) in associations of gentleman scientists. Scientific findings were transmitted primarily in writing; consequently,

> didactic instruction was more important in the education of scientists than in the training of artisans. The associations between scientists and craftsmen were further inhibited by social class divisions, with the higher social status usually ascribed to persons who "worked with their minds" (pp. 13–14).

These social divisions began to blur in the 18th century. Calder (1963) tells the story of the Lunar Society, an extraordinary group of 18th century intellectuals who met monthly (during the full moon) in Birmingham to discuss scientific and technological topics. Members included Benjamin Franklin, Erasmus Darwin (the grandfather of Charles), William Small, Josiah Wedgwood (the famous potter) and Sir William Herschel (the Royal Astronomer). Watt's model steam engine was turned into a commercial full-scale machine in the workshops of Boulton; it was Small, carrying a letter from Franklin, who introduced Boulton to Watt. Another member of the

Society, Wilkinson, made cannon balls; his accurate lathes were essential for building the engine. Wedgwood helped Joseph Priestley to obtain a position which would allow him to pursue his chemical research, and learned ways of improving his pottery. Wedgwood's invention of a scientific instrument (the pyrometer) gained him membership of the Royal Society. A society in which men of science talked with men who made things would have been inconceivable in ancient Greece, Rome, or medieval England.

The evolution of technology from a craft into a profession occurred during this time, in the late 18th and the early 19th centuries, although, as Kranzberg (1963) notes, 'this transition has never been wholly complete [and] empiricism still plays a large role in modern technology' (p. 136). The new facilities and resources that accompanied this evolution – laboratories, journals, professional societies – reflected a substantial gain in social status for technologists. Groups containing people with scientific and technical backgrounds began to assemble under the one roof to develop technological innovations. The Boulton-Watt workshop, in which a group of technicians worked under James Watt's direction, was a portent of this development. A century later, Thomas Edison's Menlo Park laboratory, where hundreds of new ideas were conceived and systematically investigated, was the fore-runner of the modern industrial research and development facility. As Gilfillan (1960, pp. 207–208) observes, 'Inventing is old and science is old, but scientific inventing in laboratories is a new thing on the face of the earth.'

In the 20th century, the industrial R&D laboratory evolved into a place where technologists and scientists would work together in inter-disciplinary teams on specific problems. Brooks (1965) identifies 'the gradual translation and diffusion of *people* from science into technology' as an essential factor in the relationship between the two fields. Smith (1961, p. 366) describes the beneficial results of contacts between metallurgists and physicists on various projects during the second world war, with physical theories influencing the thinking of metallurgists, and metallurgical facts becoming of interest to physicists. Rabi (1965) makes a similar point in referring to the emergence of a new phenomenon in the US, namely

> the practice of scientists and engineers getting together and forming small companies for specific purposes. There are any number of these specialized firms. Various associates of one of those companies, for example, produced the Klystron (p. 16).

Edwin Layton (1977) also notes the effects of such new forms of social organisation on the process of innovation. He comments that although the growth of science-based industries in the 19th century led to the widespread acceptance of the idea that technology was applied science,

> rather paradoxically, when attempts have been made to apply this model of science-technology relations to historical case studies, they have frequently failed. Historians of technology have virtually abandoned this model, since it is seldom helpful in understanding technological development. Thus, the invention of the transistor, though it involved science in rather fundamental ways, cannot be explained simply as an application of preceding advances in science. . . . The work on it was done by an inter-disciplinary team which

> included both physicists and engineers. Attempting to divide the credit for this innovation between two neat compartments is just not possible if one knows enough of the actual circumstances (p. 208).

Interacting communities with differing values

These stories from the history of technology and science tell of convergence, of two distinct social groups coming together to work co-operatively on problems of common concern. The interactions between modern scientists and technologists are so extensive, especially in hi-tech areas such as computing and bio-engineering, that it is sometimes difficult to distinguish scientific and technological work. And yet, differences remain. Scientists and technologists may share common interests, but they may also express those interests differently and hold to differing values. Multhauf (1959), an early exponent of this idea, notes the closeness of modern science and technology, asks whether there is any difference any more, and ultimately concludes that there is:

> The traditional distinction between knowledge and utility becomes somewhat shaky when subjected to close scrutiny. The association of science with discoveries and technology with inventions is even less reliable. Yet one who studies the history of the subject is left with the feeling that, in scientists and improvers of technology, he is dealing with two different species, interdependent and even occasionally transmutable, but persistently distinct, like land- and water-dwelling creatures (p. 44).

Layton (1977), in his discussion of the development of the transistor, explains that the 'divisions between science and technology are not between the abstract functions of knowing and doing. Rather, they are social; they are between communities that value knowing and doing, respectively' (p. 209). The traditional view of science-technology relationships, he argued in an earlier paper, was

> not so much false as misleading. It assumes that science and technology represent different functions performed by the same community. But a fundamental fact is that they constitute different communities, each with its own goals and systems of values. They are, of course, similar in that both deal with matter and energy. But these similarities should not be overstated. Each community has its own social controls – such as its reward system – which tend to focus the work of each on its own needs. These needs determine not only the objects of concern, but the 'language' in which they are discussed. These needs may overlap; but it would be surprising if this were a very frequent occurrence. One would expect in the normal case science would beget more science, and technology would lead to further technology (E. Layton, 1971, p. 565).

During the 19th and 20th centuries, Layton argues, technology developed into a 'mirror-image twin' of science:

> while the two communities shared many of the same values, they reversed their rank order. In the physical sciences the highest prestige went to the most abstract and general – that is the mathematical theorists from Newton to Einstein. Instrumentation and applications generally ranked lowest. In the technological community the successful designer or builder ranked highest, the "mere" theorist ranked lowest. These differences are inherent

> in the ends pursued by the two communities: scientists seek to know, technologists to do. These values influence not only the status of occupational specialists, but the nature of the work done and the 'language' in which that work is expressed (p. 576).

Values are not, however, determined solely by the social relations within a professional group. Rabi (1965) suggests that cultural beliefs about social organisation and education also affect the process of technological development. The American valuing of teamwork, for example, has generated a climate in which complex goals can be brought to fruition through the effective co-ordination of large numbers of personnel. However, he considers that other nations (e.g. Britain and France) have been more successful in encouraging individual creative genius. Societies can also influence technological development through their educational policies. A century ago, in Germany (and some other European countries), numerous technicians were being educated who could help translate scientific discoveries into new technologies, whereas in the United States, 'a technician is a technician' (p. 28). Technicians with a strong science background were crucial to the development of the German chemical industry.

ECONOMIC CONSEQUENCES OF THE TAS VIEW

The TAS view forms part of a linear model which posits that scientific discoveries lead to technological innovations which in turn have social and environmental effects, both desirable (improved standards of living, national prosperity) and undesirable (unemployment, pollution). This model has important economic consequences, since it would seem to imply that resources must be allocated to scientific research as an essential first step if technological innovation is to follow.

If coupled with a mistaken belief that industrial applications follow easily from scientific research, the model can have serious economic repercussions. Finch (1961) asserts that British industry and living standards in the middle of the 20th century remained largely static because British scientists held such a belief, so that the process of application could be safely left to technicians and laborers. He argues that

> scientific and technical advances result in economic and material progress, in higher standards of living, only when skillfully coupled with knowledge of other, quite different but vital requirements basic to intelligent application. In sharp contrast to the scientific worker who concentrates his efforts on the study of a special segment of his field, the professional engineer must understand and give due consideration to a wide range of pertinent factors. These include not only the relative costs, qualities and special advantages of various materials and a knowledge of available resources of labor and equipment, but a careful analysis and appraisal of present and possible future economic and social needs. The techniques of design are but the tools with which the professional skill of the engineer shapes creative possibilities best to meet economic and social needs and practicalities (pp. 331–332).

There is growing recognition, however, that technological innovation is not a straightforward consequence of scientific research, and a corresponding questioning in at least some government circles of the standard utilitarian arguments of the pure science lobby. In the early 1970s, the Canadian Senate Special Committee on Science Policy issued a series of reports. MacKeracher (1985, pp. 102–103) notes that substantial evidence was presented to the Committee showing that innovation did not flow from basic research and that the main economic benefit of basic science was its contribution to the output of qualified manpower through the educational process.

A recent letter by Dack (1992), a spokesman for the Institution of Engineers, the major professional association of engineers in Australia, presents a related argument:

> Too many people fall into the trap of assuming that science and technology are a high-priority factor in determining the fate of Australian industry. They are not. It is absolute lunacy for this country to hang its future on a linear model of innovation which has scientific discovery leading to useful technology and, eventually, to a saleable product. This model works to a limited extent in agriculture and the resource-based industries. But it is wrong for manufacturing. It always has been. It has resulted in the discredited phenomenon of the "science push".

Dr. Dack went on to argue that the manufacturing sector had to address innovation in the context of 'market pull', instead of being made to feel guilty for not pursuing more local research. Although Australian science added 'massive cultural and educational value' to the nation, it was an 'unfair burden on the nation's scientists' to expect them to extend their role to industrial development; 98% of world science was being conducted overseas, and technology was being developed by companies which possessed the necessary resources.

The preceding discussion is about national policies, macro-economic concerns, but a similar point can be made about the effects of the linear model at the micro-economic level of the individual industrial firm. Perhaps I might be permitted one personal anecdote to illustrate. Late in 1991, I visited an old friend in Minneapolis and met his son-in-law, a technologist in a small, specialised company which makes motherboards for computers. There was a current crisis because the insulation material they were using was failing to meet certain specifications, threatening the very survival of the company. He told me (with a tone of voice and body language signifying disapproval) of the company president's belief that if there was a problem, one simply brought in an outside scientific consultant to provide a 'quick fix'. The son-in-law certainly did not believe that technological problems could be solved by the easy application of scientific knowledge.

Research on the economics of science-technology relations

A decade ago, Freeman (1982) observed that relatively little research had been done by economists on technological innovation. In his discussion of the relation between science and technology, he adopts a position consistent with the arguments developed in this essay. In recent times, it has become 'very much more intimate'; he uses the term 'science-related' (in preference to 'science-based') technology, in order to avoid the implication of 'an oversimplified one-way movement of ideas' (p. 16).

Quoting much earlier work by Jewkes, Sawers & Stillerman (1958), Freeman argued that the neglect by economists of this area of work was partly due to their lack of knowledge of science and technology, to their pre-occupation with trade and employment issues, and to a lack of usable statistics. However, there were other explanations as well: economists avoided the area because they

> were also the victims of their own assumptions and commitment to accepted systems of thought. These tended to treat the flow of new knowledge, of inventions and innovations, as outside the framework of economic models, or more strictly, as "exogenous variables". A large body of economic theory was concerned with short-term analysis of fluctuations in supply and demand for goods and services. Although very useful for many purposes, these models usually excluded changes in the technological and social framework from consideration, under the traditional *ceteris paribus* assumption ("other things being equal"). Even when, in the 1950s, economists increasingly turned their attention to problems of economic growth, the screening off of "other things" was largely maintained, and attention was concentrated on the traditional inputs of capital and labour, with "technical progress" as a "residual" factor embracing all other contributions to growth, such as education, management and technological innovation (p. 4).

Freeman argued that these so-called residual factors are in fact basic to economic growth, whereas capital investment is only an intermediate factor. The investment process, in his view, was 'as much one of the production and distribution of *knowledge* as the production and use of capital goods, which merely embody the advance of science and technology' (p. 4). This has been recognised in most developed countries, where fundamental changes have occurred during the past generation. He cites studies indicating that in the United States, from about 1960 to 1980, the proportion of all workers engaged in 'information occupations' (education, research, development, information technology and publishing) rose from a quarter to a half.

Freeman traced the origins of research and development from the early nineteenth century laboratories established by governments and universities, through the first R&D labs established by industries in the 1870s, to modern R&D facilities which are responsible for a large proportion of new materials, products, processes and systems, and are the 'ultimate source of economic advance' (p. 5). He cites the early research of Schumpeter (1912), who developed a theory of economic development in which he distinguished between *inventions* (ideas, sketches, models for improved devices, products, processes or systems) and *innovations* (their embodiment in commercial form). Schumpeter, in Freeman's view, rightly recognised the centrality of innovation to economic progress, but tended to ignore invention as an exogenous variable.

Freeman observed that the chain of events from invention to innovation was 'often long and hazardous' (p. 7). This was largely the result of the many complex difficulties that often had to be overcome to turn an idea into a commercial operation: e.g. the need to train specialist labour, to develop mass production methods, to develop continuous flow (rather than batch production) methods to improve efficiency, to integrate electronic control devices with mechanical devices. Freeman was critical of biographical studies which over-emphasised the role of 'random accidental factors in the inventive and innovative process'; such studies help to reinforce the misconception that technological inventiveness is an exogenous variable which is largely uncontrollable.

Treating R&D as an exogenous and uncontrollable force i.e. an entity which operates independently of policy, has (Freeman believes) 'been promoted in the past by both economists and scientists, though for different reasons' (p. 14). Science and technology is regarded as a 'black box/magic wand', a view which suits scientists who simply want to pursue their research and who dislike political interference with it. It also fits the views of economists who hold to a free-market view of the economy: in the extreme view, let market forces determine how much money should be spent on technological R&D, without any government intervention. It is not a view that Freeman supports; one of its consequences is a separation between scientists/ technologists and society, with the possibility of much misunderstanding and even hostility.

IMPLICATIONS FOR EDUCATION

Revision of curriculum content

The story of the relationship between science and technology also has implications for education. The central one is the dominant theme of this whole essay: that curriculum content itself – the way in which the story of the relationship is presented to students at school and at university – needs to be reconsidered. Most teachers of technology or science are not exposed to the historical and philosophical foundations of their disciplines, either in their under-graduate years or subsequently; neither are the university and college lecturers who teach them. School textbooks commonly present factual material as a rhetoric of conclusions, or in some of the more modern texts, make reference to social and environmental issues related to science and technology, but the internal relationships between science and technology are ignored or treated superficially. One effect of the TAS view can be seen in those school textbooks which present technological artefacts as if they were simply applications of scientific principles. Projecting the story of technological development through the lens of science may also present a seriously distorted view of the nature of technology; the emphasis on laws and theories may result in a failure to consider design and problem-solving. (For a critique along these lines of a secondary school science-technology-society course, see Gardner, 1993.) The whole of the present essay reflects an intention to lay out for those interested in science and technology education the foundations for telling a more sophisticated story and thus replace an outmoded and discredited (but still powerfully held) view.

Science as gate-keeper

An educational consequence of the TAS view is to cast science in the role of gate-keeper to admission into technological careers. This sends signals to students that science is more important than technology, that the verbal and symbolic skills so highly prized in school science studies are believed to provide a better preparation for later careers than the design and making skills that might be learned in a technology course. Norman (1985) discusses the admissions policies of universities in England and Wales, and notes that 'Technical and vocational subjects, especially those involving a strong element of practical skill, have been virtually outlawed by the universities'. In that year, the Standing Committee on University Entrance in England advised sixth-formers against taking 'unconventional' A-level subjects such as Design and Technology or Electronics if they intended to apply for university admission (Penfold, 1988).

In Victoria, Australia, a government-sponsored report on science and technology education seems to have been guided by similar beliefs. After referring to government policies intended to promote international competitiveness, the report states that these policies demand

> an increasing pool of graduates trained in science, mathematics and technology and a more highly skilled workforce educated in these subjects. To improve the supply of such graduates, an increasing supply of quality students from secondary schools will be needed. These students will need to study subjects such as *physics, chemistry, computer science and higher mathematics*. The secondary school is a fundamental link in the chain (Baklien, 1987, p. 1; emphasis added).

A US government sponsored report (National Science Foundation & Department of Education, 1980) made exactly the same assumption about the gate-keeper role of science (and mathematics); note the *absence* of any mention of technological capability as useful for later engineering studies. Secondary schools of the US were called upon to

> * Generate a sufficiently large pool of people, adequately educated in science and mathematics, from which may be drawn: (a) the relatively few talented and committed students who will go on to become professional scientists and engineers; (b) future non-science professionals such as lawyers, journalists and managers who will require considerable levels of sophistication in scientific and technological matters; and (c) future technicians and members of the skilled work force who will pursue their occupations in an increasingly technological economy.
> * Provide all students with sufficient access to education in science and mathematics to allow them to pursue these different career options.

A decade later, there is little evidence that this view has changed in the US. A national report (Carnegie Commission, 1991) notes that the national interest 'is strongly bound up in the ability of Americans to compete technologically' (p. 15) yet the immediately preceding sentence – and the thrust of the whole report – refers to 'inadequacies in pre-college math and science education'. The evidence used to illustrate the contention that there is a crisis in science and mathematics education refers to lack of knowledge and misconceptions in these fields. The report called for priority attention to 'quantitative problem-solving, reasoning and basic scientific understanding' (p. 32). Although the terms 'technology' and 'engineering' are occasionally mentioned in the report, there is no real analysis of what learner capabilities ought to be developed in order to strengthen American technological competence; the assumption that mathematical and scientific abilities are not only necessary but sufficient seems to be taken for granted. As a document about mathematics and science education, it is a very thoughtful and sensible report, but there is little reason to expect it to achieve much if the espoused goal of technological competiveness is to be taken seriously. The final report of the Carnegie Commission (1993) is entitled *Science, Technology and Government for a Changing World,* yet the four-page section on K-12 education refers exclusively to mathematics and science education. The word 'technology' does not appear even once.

The Victorian report specifically mentions hi-tech fields such as information technology, biotechnology, micro-electronics and advanced materials, and obviously a strong science background is needed for technological development in such fields. There can also be little argument that more students should be encouraged to study the physical sciences. However, the implicit assumption that a scientific background is essential for *all* technological fields seems dubious. Technology is much broader than high technology. A curriculum policy grounded upon such an assumption could result in the exclusion of able students with strengths in creative problem-solving, design and manufacture who are not particularly interested at the moment in the abstractions of science. (Some may become interested later, when they may discover the need for specific scientific information to help solve a particular technological problem.) The pool of potential technologists may be diminished if the gates are closed too early.

Another consequence of casting pure science in the role of gate-keeper is to leave those high school graduates who will not be proceeding to careers in technology with a narrow view of this central aspect of modern culture. George (1981), an engineer, criticised secondary school curricula in which

> young students are taught physics, chemistry and biology as abstract, self-significant science which understandably come to represent the whole of science in their minds . . . Engineering and the work of engineers remains obscure. At best, engineers are thought to apply science (physics, chemistry, biology) and mathematics to some practical ends. Technology is perhaps seen as the result of this application of science, and perhaps thought to be dangerous, too (pp. 25–26).

He concluded that students typically ended their secondary education 'with a distorted view of science and virtually no concept of engineering and technology' (p. 26). George was writing about education in Canada a decade ago, but his criticisms still apply today, in that country and in many others.

Implications for teacher education and teacher development

Evidence for the persistence of the TAS view among practising teachers can be seen in some recent research on teachers' perceptions of the nature of technology. Jones & Carr (1992) interviewed 30 primary and secondary teachers in New Zealand. The five science teachers in the sample all held similar views, namely that technology involved the application of science, and that technology was a vehicle for teaching science. Virtually all the teachers viewed technology education from the vantage point of their own background, which is not surprising. Thus social studies teachers focussed on the skills needed for living in a technological society; a technical teacher with a trade background saw his function as teaching manual skills; several primary teachers took 'technology education' to mean the use of computers for mathematics and language development. The authors note that not one teacher in their sample had a broad view of the nature of technology. Clearly, with technology education emerging as a major area of curriculum reform in many parts of the world, there will be an urgent need to help existing and future teachers (of science and of other fields) to develop a richer and deeper understanding of the nature of technology.

The issue is not merely a cognitive one. Teachers' beliefs about science-technology relationships may affect their feelings of competence when they are called upon to introduce new material into the curriculum. Most primary school teachers are females; only a minority of females study physical sciences. Hence many primary teachers feel apprehensive about introducing physical science content into the primary school. If teachers who harbour such feelings also believe that technology is applied (physical) science, then this lack of confidence may well generalise to technology as well. Schaverien & Cosgrove (1992) have identified such beliefs and attitudes among practising primary school teachers in N.S.W., Australia; the researchers adopt the language of Karl Popper to describe these teachers as prisoners caught in the frameworks of their theories. These authors have worked with small groups of teachers in an attempt to change their frameworks, by presenting them with technological design problems (e.g. devise a system using LEGO-LOGO for controlling the lighting sequence in a set of traffic lights) which the teachers are capable of doing, without years of study of physical science at school or university. They report that the teachers became 'self-directing, challenged and fulfilled and they developed feelings of control over the technology' [published abstract of their oral presentation]. In the language of the present essay, science for these teachers was not a gateway to technology, but a hurdle which could be removed by demonstrating, through their own practice, that it was unnecessary for achieving technological capability. In describing their in-service work with teachers, Schaverien and Cosgrove are quite explicit about their attempt to help teachers break free of their restrictive framework of theories and find – Popper's term again – a better and roomier one.

Clearly, if the study of technology is to be improved and its relation to science to be more accurately portrayed, there is a long agenda for consideration by educational policy-makers, curriculum developers, teachers, academics, teacher educators and textbook writers.

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