Has Science Created Technology?

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SINCE the days of Bacon, and certainly since the creation of the Royal Society—which some at least of its founders intended should realise the vision of the House of Salomon in Bacon's *New Atlantis*—science has been presented to the general public as the prime source of inventions which would utterly transform human life for the better. No one individual can be held responsible for launching the idea that science will lay a succession of golden eggs, and that society should pay to understand how nature works in order to exploit the potentialities of nature. But the team of scholars of Salomon's House was to include a group who "bend themselves, looking into the experiments of their fellows, and cast about how to draw out of them things of use and practice for man's life and knowledge . . . These we call dowry-men or Benefactors".[1]

This expectation that such dowry-men will find plenty to employ them has continued in force, and still flourishes. Bacon apparently reasoned: from the carcasses of an obscure kind of maggot, we can extract a cloth finer, smoother, more glistening than any other; from a mush of old rags, we produce a smooth white sheet, the best surface for showing clear marks of writing or drawing; from the scraping of cowsheds, from sulphur, and charred wood a powder with powers of violence greater than any mechanical blow. All these inventions had been made since the end of the Roman empire, to which Bacon's generation still looked for their standards of culture and social order. So, for the previous century at the least, there had been a growing sense that for all its grandeur this civilisation of antiquity lacked several techniques now available; and all, it was presumed, had been discovered by accident. If only we understood the basic forms of natural things, surely many more new substances and forces would be at our disposal? If we knew better the forms that operate in our own bodies, medicine would at last be able to cope with many diseases before which it was now helpless. Perhaps alchemy provided Bacon with an example. Alchemists were working on a theory of matter, and supposed that if their assumptions about matter were correct, they would be able to devise elixirs and marvellous cures, raise the character of base metal to gold, produce solvents that would part the inner essences from external accidents. It may be that—as Bacon's contemporaries believed—gunpowder was discovered

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[1] Bacon, Francis, *The New Atlantis* (London: 1635). p. 44. Bacon should not be seen as the "onlie begetter" of this doctrine, but as its leading exponent; nor did he consider the scientific pursuit worthy only if undertaken in hope of technological fruit. There has been a tendency to stress this aspect of his ideas: e.g., Farrington, B., *Francis Bacon, Philosopher of Industrial Science* (London: Lawrence & Wishart, 1951); such a view is qualified in e.g., Rossi, P., *Francesco Bacone: dalla Magia alla Scienza* (Bari: Laterza, 1957; English trans., *Francis Bacon: From Magic to Science* (London: Routledge & Kegan Paul, 1968).

in the course of alchemical experiments. Much earlier, incendiary mixtures like Greek fire had enriched the medieval arsenal with weapons derived from such research. Distillation too first appeared in alchemical manuscripts; probably the inventors were not looking for a more potent drink than wine, but for the inner nature of wine. Names like "spirits of wine" for alcohol, or "spirits of salt", are products of the frame of mind which led to these discoveries. The principal mineral acids of later industry, like sulphuric acid (as oil of vitriol) or nitric acid (as aqua fortis) were thus the product of investigations based on theories, which were believed to lead the operator to new and remarkable powers.[2] The fact that the theory in question was poorly tested, indeed nonsense, does not alter that. Bacon saw the fallacy of alchemy; he also saw what had come out of it and could well hope that a clearer, more correct knowledge would add enormously to the techniques and materials on which these practitioners had unwittingly stumbled.

The Anticipation of Material Benefit from Scientific Knowledge

In the eyes of many seventeenth-century men, however, mathematics promised much more than the investigation of forms, as proposed by Bacon. That might even be a more credible antecedent than alchemy, for there was already a vigorous movement urging the increased use of mathematics to improve all the arts. There was nothing novel in this. Among the oldest relics of any kind of writing are inventories, lists of quantities, designs, maps—all signs in which geometrical or arithmetical symbolism came to the aid of words. An early legend claimed that ancient Egyptians invented geometry to restore the boundaries of fields submerged in Nile floods. One of the oldest of all portrait-statues shows a Sumerian princeling on whose lap is laid a plan. For the erection of pyramids and palaces and temples, for the survey of estates, lands, cadasters of property, the routing of conduits to supply water for irrigation as well as for draining—for all these, some elementary mathematics had to be employed. In these early civilisations, counting, measuring and planning were primary features of the hydraulic culture's bureaucracy. These activities also aroused suspicion among the ruled classes from the first, as is recalled in the biblical curse against censuses. One could trace these pursuits across the history of many civilisations, through the geometrical character of Hellenic architecture, the awe for mathematics and its applications reflected in the tales of Archytas and his mechanical dove, or Archimedes and the wonderful engines he designed in the hope of saving his native Syracuse from the Roman army. Nevertheless, there was also an attitude of doubt that felt these inventions were unworthy of the true mathematician. The disdain of the machine as some kind of mathematical marvel, which Aristophanes and Plato expressed, remained the view of the majority in antiquity, and Hellenistic innovations of great consequence, such as the water-mill, the gear and the screw-press, appeared without benefit of

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[2] Multhauf, R. E., *The Origins of Chemistry* London: Oldbourne, 1966), esp. pp. 179–211.

mathematicians. Even the Archimedean screw seems to be older than Archimedes, the creation of an ingenious unknown subject of the Ptolemies rather than the famous geometer.

All the same, mathematician and magician came to be almost synonymous in medieval times, and the link was strengthened by the association of both with astrology. In the Renaissance, however, the appeal to mathematics as the key to all knowledge, the one certain and reliable secular science, was heard loudly and clearly. Mathematical techniques, it was thought, could be used to make more reliable artefacts, based on these same certain principles. Hence Leonardo da Vinci's dictum that mechanics is the paradise of the mathematical sciences, the fruit of the tree of mathematics. Leonardo's own knowledge of mathematics may have been limited; the ideal he expressed already prevailed. In this world regularity, permanence, simplicity derive from mathematics; once true, it was always true, because it followed necessarily from necessary axioms. Artillery imposed a geometrical style of fortification; discovery and navigation sought a sure guide across little known lands and oceans and found it in the geometrical rules of cartography and the haven-finding art. Perhaps too the historical accident of inflation and the throwing of new land on the market by reason of the dissolution of the monasteries and the acquisition of so much property by new masters made evident the need for mathematical surveyors. There were good economic and political reasons why the status of mathematics, which had been the esoteric pursuit of a handful of somewhat mysterious and even dubious investigators became the cherished possession of a sizeable class.

In the 1560s men like Ramus found a public platform to preach the expansion of the teaching of mathematics, so as to improve all trades and arts.[3] This doctrine also introduced the literature of mechanical invention, beginning with the *Livre des machines* of the French Huguenot mathematics teacher and distiller of essences, Jacques Besson, and the lavish work of the Italian military engineer, Agostino Ramelli; both saw a large number of wonderful new inventions as the fruit of mathematical art.[4] These ideas combined with the tantalising promises of alchemists—if only the true nature of substances could be worked out—to feed the appetites of philosophers and projectors alike in the seventeenth century. The scientific movement, under way by the time of Bacon, triumphed in the 1660s. Without wishing to play down the intellectual curiosity that motivated most of the great men of the movement, I would hold that even they usually shared the vision of wealth and health through ever-growing realms of knowledge. The founders of the Royal Society hoped to draw up histories of trades, with a view to the improvement of their practice through the new philosophy.

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[3] Ramus, P., *Prooemium Mathematicum* (Paris: 1567); *Scholae Mathematicae* (Basle: 1569).

[4] Besson, Jacques, *Livre Prémier des Instruments Mathematiques et Mecaniques . . . par Jacques Besson, professeur et ingénieux és sciences mathematiques* (Paris(?), 1570–2?); and Ramelli, Agostino, *Le Diverse et Artifitiose Machine del Capitano Agostino Ramelli, ingeniero* (Paris: 1588) were the forerunners of quite an extensive literature. See also Keller, A. G., *A Theatre of Machines* (London: Chapman & Hall, 1964).

How important was this motive? Although there has been much assiduous collection and analysis of data, the question remains open; and still it haunts the historiography of the scientific revolution of the seventeenth century with uneasy thoughts. Marxist historians—and not only Marxists, but all those chiefly interested in establishing how men were recruited to the ranks of the new sciences—can easily find such motives in economic interests that wanted a better pump to drain waterlogged mines, better ships, dredges, machines and manufacturing processes.[5] Against this school, its antithesis has duly arisen: those who stress that the real innovators in science wanted above all to shape a new way of thought.[6] For them, techniques could provide anomalies and problems to solve, or curious raw data, but that would be all. Galileo, Kepler, Huygens and Newton were, according to this view, quite simply uninterested in the advance of technique; they were driven purely by spiritual and intellectual quest. If they did occasionally suggest how some craft might be improved, it was but to impress the groundlings, or the forces of government and commerce, or maybe to earn some money to free them for the intellectual tasks which alone drew them on. Robert Boyle, Hooke and Papin, do not, however, quite fit this model. But then, those who see the scientific revolution as the advent of a new metaphysic do not take such people so seriously.

Does Technological Invention really come from Scientific Discovery?

Just as historians have been debating for at least half a century how far the new experimental–mechanical philosophy was born of the desire to make new technology out of new understanding of nature, so they have been debating the reverse side of that coin: how far the Industrial Revolution of the eighteenth century was the result of the preceding revolution in thought? Or was it the achievement of sooty empirics, who knew little of the victories of philosophic thought, and cared less? Speculations that Newcomen had been advised by Hooke, that Watt sat at the feet of Black to learn all about heat have been vigorously scotched in recent years by industrial historians. The great inventors may have been relatively unschooled, but then at that time there was not really any such thing as a "scientist". All were amateurs of one sort or another, apart from a tiny number of university teachers. Watt and Smeaton trained as mathematical instrument makers, not through academic studies but a kind of high-grade apprenticeship. Manufacturers

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[5] See Merton, Robert K, "Science, Technology and Society in Seventeenth Century England", *Osiris*, IV (1938), pp. 360–632; Hessen, B., "The Social and Economic Roots of Newton's Principia" in *Science at the Crossroads*, papers presented to the International Congress of the History of Science and Technology, by delegates of the USSR (London, 1931: reprinted, London: Cass, 1971), and Lilley, S., *Men, Machines and History* (London: Lawrence & Wishart, 1965). The debate at the end of the 1960s is summarised by Merton, in the introduction to a new edition of *Science, Technology, and Society in Seventeenth-Century England* (New York: Harper, 1970); and Hall, A. R., "Merton Revisited", *History of Science II* (1963), pp. 1–16.

[6] See Koyré, A., *Metaphysics and Measurement* (London: Chapman & Hall, 1968); also Hall, A. R., *op cit.*

were an object of active interest in the new societies, literary and philosophical, which were formed to promote the discoveries and ideals of the Enlightenment. Still, manufacturers could rarely add to the progress of science, while the more scholarly natural philosophers rarely discovered anything that could be turned to the uses of industry.

At the end of the seventeenth century, Fontenelle claimed that science would soon produce great things in the arts, but all he could claim in mechanical technology so far was the pendulum clock, with the refinements derived from Huygens's improvement of Galileo's original theory.[7] By the end of the century what more was there? When Condorcet reviewed the march of human history he felt sure that a new age was about to begin, with a political revolution which would set science free to create an era of celestial happiness. But he too found few existing science-based arts to justify his enthusiasm. Studies in hydrodynamics by Euler and the Bernoullis and even the more down to earth Parent had little direct effect on the design and construction of water-mills in Europe. Yet what should we say of a series of carefully planned experiments to test the capacities of water-wheels by varying a number of parameters by significant and precisely measured quantities? At the start of the century, the Swedish engineer Christoph Polhem arranged for just such a run of experiments to find the ideal dimensions and angle of discharge for a vertical water-wheel, at the mining centre of Falun. Different types of blade were tried, the ratio of diameters of wheel and axle was varied, as were the head and the inclination of the head race, and the wheel raised varying weights. In the end Polhem had to conclude that the measurements of time were unreliable and so he could not be sure of velocities attained by his apparatus.[8] Half a century later a similar programme was taken up in France, Britain and Germany. Smeaton's results in Britain proved the most acceptable, perhaps in part because of the simplicity of his apparatus, and they were allowed a definitive character they did not wholly merit.[9] But is this activity science, or had practical technology just learnt the concept of the precise controlled experiment, just as science had learnt from the practical arts the principle of "try it and see"? Professor D. S. Cardwell indeed has shown how ideas on input–output power ratios, intended for water-wheels, were to influence those who tried to explain and improve the steam engine.[10] Watt's researches appear largely independent of current theory; he had to hunt for the information he needed since it could not be found either in the scientific literature of the time, nor could it be dispensed by the natural philosophers who in his early days employed him and were in a sense his patrons.

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[7] Fontenelle, B. de., "Préface sur l'Utilité des Mathématiques et de la Physique, et sur les Travaux de l'Académie des Sciences", preface to *Histoire du Renouvellement de l'Académie Royale des Sciences*, in *Oeuvres de Monsieur de Fontenelle* Paris: Brunet, 1752), V, esp. p. 9.

[8] Lindqvist, S., *Technology on Trial: Uppsala Studies in History of Science I* (Uppsala: Almqvist & Wiksell International, 1984), esp. pp. 67–74.

[9] Reynolds, T., "Scientific Influences in Technology: The Case of the Overshot Waterwheel, 1752–1754", *Technology and Culture*, XX (1979), pp. 270–294.

[10] Cardwell, D. S. L., "Science and the Steam Engine Reconsidered", *Transactions of the Newcomen Society*, XLIX (1977–78), pp. 111–120.

Robert Multhauf has examined the same principles at work in the chemical industry of the eighteenth century, for instance, in relation to the manufacture of sal ammoniac.[11] Once again the outcome remains ambiguous. How far did theoretical concepts affect innovation in chemical technique? How far did they simply lead to the careful checking, and perhaps eventually the abandonment, of traditional recipes of long standing? Certainly the chemistry of the eighteenth century could not do much to explain how processes worked, so that new processes were almost always conceived by men steeped in the methods of their craft. Likewise, Professor Charles Gillispie has argued that the Leblanc process was not the result of Leblanc's application of new theories in chemistry but, if anything, inspired by recent developments in ferrous metallurgy, apparently as innocent of new fundamental knowledge about materials as was his own invention.[12] But even a little knowledge of the theory of materials might give some advantage. However, natural philosophy before Lavoisier lacked a commanding paradigm that could be realised in chemistry, so in reality there was not much difference between mere empirical practice and mere knowledge of the changes induced by established practices. Where theories existed they now look quite inadequate, and have long been jettisoned.

So the prolonged debate over the role of science in the Industrial Revolution has not led to any generally accepted conclusions. As Professor A. R. Hall, a leading participant, has pointed out, the argument is like that between nominalists and realists rather than about the facts.[13] How should we interpret and correctly describe these forms of behaviour? Can we say there is a connection between "science" and "practical technology" if manufacturers correspond with "scientists", or carry out experiments at their works, especially when that is done without any clear commercial objective? Is all research impelled by curiosity science? Is all industrial research concerned with industrial processes technology? If we were to phrase the question strictly in terms of a debt of the Industrial Revolution to the ideas of the new science, we might find little positive to propose. How could Newton's *Principia* be turned into engines? Even if Newton does suggest that some of his theorems could be of use in ship construction, that was probably just a friendly gesture. So the tendency is to look in a different area. Josiah Wedgwood encouraged the adoption of scientific attitudes and was active in the diffusion of scientific knowledge. But did he make practical use of new theories? Actually he saw himself as standing on the side of science of the divide. After consulting a Liverpool glassmaker on some experiments he had planned, Wedgwood commented that "to make myself

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[11] Multhauf, R. K., "Sal Ammoniac: A Case History in Industrialization", *Technology and Culture*, VI (Fall 1965), pp. 569–583.

[12] Gillispie, C. C., "The Discovery of the Leblanc Process", *Isis*, XLVIII (June 1957), pp. 152–170.

[13] Hall, A. R., "What did the Industrial Revolution Owe to Science?", in McKendrick, N. (ed.), *Historical Perspectives: Studies in English Thought and Society in Honour of J. H. Plumb* (London: Europa, 1974), p. 129.

understood I did not find so easy as one would imagine—owing chiefly to my not understanding sufficiently the technical nor the philosophical terms, so that in fact we spoke two languages".[14] Now is Wedgwood the recipient of science's largesse if he talks this philosophical language? Or if he undertakes a prolonged series of experiments to establish a pyrometric scale? That is why it is tempting to dismiss the whole issue as merely semantic. Or should we think rather of an increasingly common state of mind first nurtured by the mathematical enthusiasm of the sixteenth century, firmly, indeed militantly inculcated by the mechanical philosophers of the late seventeenth? This state of mind calls for progress, scrapping old ideas, testing established practice, applying strict numerical accounting and controlled, precise experiment—in theoretical science and technology alike. So Professor Gillespie decides that "the two main departments of technical activity"—science and industry—"are distinct but related". Buchanan takes up this theme of "distinct but related" when he presents us with a "Promethean revolution", in which we cease to argue whether the technological egg came before the theoretical hen, or vice versa, but see both as aspects of one surge towards the increase and aggrandisement of the human empire over nature, whether the objective be public knowledge or private gain from new products and processes. They are, in this view, two prongs of a single fork.[15]

Lavoisier no doubt had a similar "distinct but related" view in mind, when he tried to save his beloved Académie des sciences from being submerged in a general association for the promotion of all arts and sciences.

> The spirit which guides scientists . . . is not the same as that which guides and should guide those engaged in the practical arts. The scientist works only in response to his devotion to the sciences and to add to the reputation he enjoys. When he makes a discovery, he hastens to publish it and his objective is attained if he is accorded the credit for it and if it is genuinely confirmed that he has made it. The person working in the practical arts, in contrast with the scientist, whether in his own investigations or in the use he makes of the investigations of others, always has a chance of a practical benefit in view; he publishes only what he cannot keep to himself, he reports only what he cannot keep secret.[16]

This is what Lavoisier wrote when he urged the revolutionary leaders to leave the savants of the Académie to pursue pure science wheresoever the intellectual chase should lead them. They could examine the practical but speculative inventions of the *artistes*—those engaged in the practical arts—and show them where these inventions have gone wrong and had failed to perform as expected because of particular natural laws. But they should not be expected to produce any inventions themselves. Of course, he

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[14] Quoted by McKendrick, N., "The Role of Science in the Industrial Revolution; A Study of Josiah Wedgwood as a Scientist and Industrial Chemist", in Teich, M. and Young, R. (eds), *Changing Perspectives in the History of Science: Essays in Honour of Joseph Needham* (London: Heinemann, 1973), p. 296.

[15] Buchanan, R. A., "The Promethean Revolution: Science, Technology and History", in Hall, A. R. and Smith, N. (eds), *History of Technology: First Annual Volume 1976* (London: Mansell, 1976), pp. 73–84.

[16] Lavoisier, A. L., *Oeuvres*, IV (Paris: Imprimerie Imperiale, 1868), letter to M. Lakanal, 18 July, 1793, pp. 623–624.

understandably ignored his own work for the gunpowder commission, where he had put his own chemical knowledge to account, to the end of increasing the production of saltpetre, or even replacing it. Understandably, too, the *artistes* were often irked by the attitude of the scientists, who passed their clever motions through a critical mangle, *de haut en bas*. As Professor Gillispie remarks, that may well have contributed to the unpopularity of the Académie, and the downfall of Lavoisier.[17] The French Revolution, which eventually cut off Lavoisier's head, rejected his vision of science and technology as independent kindred.

Growing Confidence in the Construction of Technology from Scientific Knowledge

The new regime was convinced it could realise the dreams of *The New Atlantis*; and if asked what use the Republic had for these clever scientists, answered, none—unless they devoted their talents to discovery which led directly to application. The political transformation brought about another revolution, in education, to ensure that scientific knowledge would be so taught as to reform all arts and crafts. But however democratic this was supposed to be, the crowning glory of the new system in the end was a *polytechnique*, to train a new elite—a true aristocracy of scientific and technological talent, engineers, administrators. Over the next decades, other countries soon followed similar patterns of change. Hence, whatever might be the case in the previous centuries, all seem agreed on the mutual dependence of science and technical innovation through the nineteenth century. Some of those who most stress the earlier separateness are most keen to show convergence and interlocking at this later stage. Electrical engineering from the telegraph on must depend on prior demonstration of the laws of electrodynamics in the first quarter of the century. Without Volta, Davy, Oersted, Ohm, Ampère and Faraday, there would have been no telegraph, telephone, electrolysis, electroplating, no batteries, generators, illumination or trams. Within months of the exposition of the principles of induction on which a motor could be based, a motor was duly built by an ingenious artisan, Hippolyte Pixii.

So a new industry was born directly out of basic theory. It was supposed to be the same story with chemistry. In or out of polytechnics and universities, a succession of new industries arose, new synthetic dyestuffs, new explosives, artifical materials like parkesine, celluloid, in the next century bakelite. Just about everybody agreed that chemical science provided the basic ideas which chemical manufacturers applied. Similarly the internal combustion engine was presumed to have been inspired by mid-century thermodynamics; then followed the revolution in transportation which the internal combustion petrol engine and electric power made possible. This connection drove all independent states to invest ever larger sums in new universities

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[17] Gillispie, C. C., "The Natural History of Industry", *Isis*, XLVIII (December 1957), p. 401.

and polytechnics and trade schools. Paradoxically, the state which had been the pioneer was not doing so well. French industry lagged behind that of Germany, as in the eighteenth century it had lagged behind Britain. The reaction of the French was to put more effort into more of the same education and keep an eye on how the Germans were running their system.

With the invention of radiography following a matter of weeks, if not days, upon the discovery of X-rays, with the new wireless telegraphy supposedly taken from the theories of Maxwell by way of the theoretical demonstration of long wave electromagnetic radiation by Hertz, it was reasonable to say that the time had at last arrived when science and technology were one—and joined as one in their success. A new century opened with excited anticipation. In the event, some of the leading inventions of the twentieth century have been the reverse of utopian—still, the atom bomb could be said to mark the culmination of the belief that all humanity need do is put its best brains on a subject, any subject, and then the sky is not the limit. From now on, nothing will be impossible. After the post-war recovery and a new boom, the 1960s were an age of optimism, not to say complacency. The gap in time, it was said, between scientific discovery and technical application was shrinking rapidly. It had been diminishing by a simple arithmetical progression since the eighteenth century. Now the gap had all but disappeared. A glorious future was predictable, based on the immediate application of new ideas pouring forth upon a happy, hedonistic, ever healthier world.

The Enthusiastic Coupling and Identification of Science and Technology

The public, or more specifically, the public's embodiment in the various nation-states, has then come to believe most firmly that science is a goose that is constantly laying golden eggs, but will die unless kept well fed. However, specially since the Second World War, science has been costing a lot of money. On the assumption that "science discovers, technology applies" it must be well worthwhile to invest these sums in science, since from the scientist's basic investigations guided by his curiosity, new technology will eventually flow in an unending stream. In a passage that became a *bête noire* to his critics, Vannevar Bush, President Roosevelt's science adviser, urged that "basic research . . . creates the fund from which the practical applications of science must be drawn", and that "new products and new processes . . . are founded on new principles and new conceptions which in turn are painstakingly developed by research in the purest realms of science".[18] These words appear in a report, originally to the President, which was first published as *Science, the Endless Frontier* in 1945. Bush's views certainly helped to inspire the setting up of the National Science Foundation in America. In Britain. P. M. S. Blackett, then president of the Royal

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[18] Bush, V., *Science, the Endless Frontier; A Report to the President* (Washington: Office of Scientific Research and Development, 1945), pp. 13–14.

Society, submitted a memorandum to Parliament on the wisest placement of research funds. By way of introduction, he set out a "simplified schematic form" of innovation in technology: "pure science, applied science, invention, development, prototype construction, production, marketing, sales and profit".[19]

The train of thought might be: Clerk Maxwell, basic physicist and lofty thinker, had the fundamental concept of electromagnetic radiation outside the wavelengths of visible light and the ultraviolet and infrared bands immediately adjacent; Hertz proved him right experimentally; this was turned into a medium of communication by Marconi, and so radio was born. Or: Röntgen discovered X-rays in the course of investigation into the nature of cathode rays, but like Hertz and Maxwell he was interested first and foremost in the theory of light and comparable radiations, and in their relationship to other electric phenomena; then technologists seized on Röntgen's X-ray pictures, for him an experimental demonstration, to use as a technique of medical inquiry into injuries hidden from the naked eye by the opacity of flesh. Or: the discovery of X-rays led to the discovery of radioactivity, and ultimately of the atomic nucleus and its structure; this was taken over by technologists, who turned the theoretical concept of a potentially unstable nucleus into nuclear bombs and nuclear power. There is indeed an even simpler popular myth which confounds the two altogether, and supposes that science both discovers and applies, which is why great scientists are often portrayed in science fiction as more wizard than sage. Still, that may be because popular imagination cannot appreciate that scientists really do find their main interest in life in the understanding of some peculiar feature of the universe, be it the nature of quarks or the evolution of quaggas.

Difficulties of Proof

That notion may lie behind some expectations from science—and its supposed production of science-based technology. But even in the more sophisticated version, it follows that economic returns would be great if our investment in basic science were greater, seeing how much has already been received serendipitously. During the 1960s several attempts were made to quantify such assumptions, and work out in precise terms what financial benefits had been obtained through industrial innovation derived from science. Some of these proved distinctly disappointing. The findings of Project Hindsight, completed in 1966 (but not published until three years later) examined 20 weapons systems introduced since the war in the armed forces of the United States. Seven hundred innovative "events" could be identified, in their development. Of these, only two had arisen from basic scientific research. Nine tenths of the remainder were strictly technological,

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[19] Blackett, P. M. S., "Memorandum to the Select Committee on Science and Technology", *Nature*, CCXIX (14 September, 1968), p. 1108.

the others "applied science". Edwin Layton remarks that this "came as something of a bombshell to the scientific community".[20] If technology is, after all, not the golden egg which is laid only by that goose—as the Bush passage implies, for instance—but is instead produced by some self-generating process within an independent technological culture, why spend so much on the purely intellectual activities of puzzle-solving fundamental science? All the more so, because although national governments may feel a duty to act as patrons of high culture now that private patrons are harder to find, there are inevitable limits. If science is beautiful, like art galleries and symphony orchestras, but not useful, should it receive so much more subsidy than they do? Smaller countries, even the poor, formerly colonial countries, were interested too. Was the solution of their problems the creation of a large pool of scientists, who would think up ideas to generate new technology and wealth at home, instead of importing scientific knowledge and technology? Or would the support of a pool of scientists be a further drain on hard-pressed economies, before the scientists were gradually drained away to centres of scientific excellence in the United States or Western Europe? It may depend however on where you start to look. The distressing conclusions of Project Hindsight were in part challenged by a report produced for the National Science Foundation, *Technology in Retrospect and Critical Events in Science*, which came out in 1968. This study looked at five inventions that everyone would regard as very much "high technology", and as very radical in their methods, from oral contraceptives by way of electron microscopes to videotape recording; it decided that seven tenths of the innovative events here came from "non-mission oriented research".[21]

Further Efforts to Demonstrate the Connection

So these two classic American studies came to opposed and in effect inconclusive results. In Great Britain the assumption had indeed been made, since the days of the Cavendish commission and its successors in the 1870s and 1880s, that more money would have to be spent on science and education in science. As the report of the Central Advisory Council for Science and Technology of 1968 put it, basic science "constitutes the fount of all new knowledge without which opportunties for further technical progress must rapidly become exhausted".[22] For that reason, such "long-term science" must be supported, the Central Advisory Council insisted, for otherwise the long time-lag between "scientific discovery" and "practical application" must make it uneconomic. In consequence, in 1969, two British

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[20] Layton, E. T., "Mirror-Image Twins: The Communities of Science and Technology in 19th Century America", *Technology and Culture*, XII (October 1971), p. 564.

[21] Langrish, J., Gibbons, M., Evans, W. G. and Jevons, F. R., *Wealth from Knowledge* (London: Macmillan, 1972), p. 34.

[22] *Technological Innovation in Britain* (London: HMSO, 1968), p. 4.

scientific civil servants, I. C. R. Byatt (senior economic adviser at the Department of Education and Science) and A. V. Cohen (scientific secretary, Council for Scientific Policy) produced, under the guidance of the late Professor Harry G. Johnson, *An Attempt to Quantify the Economic Benefits of Scientific Research*.[23] They suggested that one could assess how much an industry, or indeed eventually a national economy or the world economy, would have lost in the way of returns if a certain scientific discovery had been made later than it was. They even went so far as to set out a series of equations in which those benefits might be expressed. The principle implies tracing an unknown number of inventions and innovations that might fan out from a single scientific theory involved in any one technological innovation. In addition, any application might be delayed for an extended period, so as to deny the science its economic benefits, for industrial or social reasons, or for the want of some material with particular properties, and thus alter the assessment. They presented a diagrammatic genealogical tree for the transistor, which they took as a good example of the type of invention to which their method could be applied, but the tree turned out to have several roots as well as several branches. Two subsequent investigators, implicitly critical of the work of Byatt and Cohen, re-examined the question,[24] limiting their attention to the evolution of the transistor. They claimed that the crucial event here was the requirement for improved rectifiers for use in connection with radar during the Second World War. However, as they made little more than the bare statement that this is what happened—while most of the article is devoted to a summary of the theory underlying the transistor and the experimental apparatus used—their results were not convincing.

The United Kingdom Council for Scientific Policy did attempt to go further with the investigation initiated by Byatt and Cohen. By the end of 1970 this working group felt obliged to say that it would not be possible to relate science to the statistics of industrial benefits in any simple manner. However, at the same time a more detailed investigation was under way. This had begun at the new department of liberal studies in science at the University of Manchester in 1966. It studied all those technical innovations which received the Queen's Award for Industry in 1966 and 1967, which were the first two years of the operation of the scheme. As *Wealth from Knowledge*, it has become a classic treatment of the issues involved in technological innovation.[25] The discussion of its conclusions remains the most useful base from which further exploration can proceed.

When the team sorted their innovations into those which originated

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[23] Byatt, I. C. R. and Cohen, A. V., *An Attempt to Quantify the Economic Benefits of Scientific Research*, Science Policy Studies No. 4, Department of Education and Science (London: HMSO, 1969).

[24] Gibbons, M. and Johnson, C., "Relationship between Science and Technology", *Nature*, CCXXVII (11 July, 1970), pp. 125–127.

[25] Langrish, J., Gibbons, M., Evans, W. G. and Jevons, F. R., *Wealth from Knowledge* (London: Macmillan, 1972). The attribution of various parts of the book is made on pp. x–xi.

through "need→pull', and those from "discovery→push", and then subdivided the latter into those where the discovery was technological itself, and those where it arose in basic science, they concluded that the latter played a very modest role. Only two cases indeed seemed to them to fit the model "Science discovers, technology applies": the use of titanium alloys in aircraft, and the application of theoretical treatments of plastic flow in steel structures. Even these two only partially fitted the model.[26] Apart from that, they found that over the whole range of the twentieth century only nuclear power and silicones could be cited as examples of that effect. Still, their analyses do depend on taking this "scientific discovery→push", to mean that pure research impelled by curiosity will beget a new technology out of the blue, in an explosive and revolutionary manner. That is not the kind of innovation which would turn up in an average year to win the Queen's Award—rather, it is very much the image of nuclear power. It could be maintained that at least two thirds of the innovations dealt with by Langrish and his colleagues could hardly have been made without a theoretical understanding of the physics and chemistry or biochemistry of the substances on which the development teams were working. Thus the case of the Chorleywood breadmaking process might have been chosen to exemplify the debt of technology to biochemistry, as it uses ascorbic acid (vitamin C) as a fast-acting improver. Professor Jevons dismissed this argument, although he acknowledged that the application of ascorbic acid would have depended on research in organic chemistry in the 1930s, because he says, if vitamin C had not been available, other fast-acting improvers could have been used.[27] Touching on the same point in 1976, he said of the original vitamin C research, "some of which may have been of a curiosity-oriented nature": and as a possible alternative, he specifies "such as potassium iodate".[28] But does not the existence of potassium iodate as an alternative not also depend on many years of chemical research impelled by intellectual curiosity?

Despite these reservations about the significance of fundamental research for technological innovation, Professor Jevons insisted that there are nevertheless "three main ways in which science can bring economic benefits".[29] First, there are "mega-innovations": "scientific discoveries do occasionally lead to applications in the form of new technology; this is rare, but the effects may be multiplied indefinitely as technology builds on technology"; or, as he put it in his preface, "science is not the father of technology but an anonymous well-wisher who sends it gifts through the post . . .".[30] Secondly, there are "techniques which make it possible or easier to tackle industrial problems successfully". And finally as an "element contributing to the output of highly qualified men and women educated in

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[26] *Ibid.*, pp. 33–39, 72–77.

[27] *Ibid.*, p. 37.

[28] Jevons, F. R., "The Interaction of Science and Technology Today, or, Is Science the Mother of Invention?" *Technology and Culture*, XVII (October 1976), p. 733.

[29] Langrish, J. *et al.*, *op. cit.*, p. 42.

[30] *Ibid.*, p. xii.

science and its methods". The last might even be the most important, as new ideas penetrate the world of industry more easily "on the hoof"—in the head, rather than on paper.

Over the years, members of the group at Manchester continued to investigate the issue. Gibbons and Johnston studied the "new products" sections of British trade journals, chose 30 innovations as worth pursuing, and, by means of interviews with the key figures in the research and development of these 30, sought the sources of the 887 units of information which had played some part in this process.[31] Of these, they concluded that exactly 300 had some external source, the others coming from within the intellectual resources of the individuals and firms concerned. They found that 107 or 36 per cent of these external units of information came either from the scientific literature, or from scientific handbooks dealing with research into general laws, and the properties of particular natural substances, as opposed to a technical literature concerned with artefacts and processes; or else from contact with scientists in universities or government research institutes. Thus just over a third of the information which went to the making of the 30 innovations came from scientific sources rather than from technological ones—and a third of those from links with universities. As one of their informants said, "Whenever we had a knotty problem, I knew I could always go up to the uni and talk it over with the electronics people I knew from the old days, and what's more use their equipment and library".[32] This flow from academic science is thus continuous. But, it might be said, much of that might also be technological—some universities are actually called "institutes of science and technology". There is a tendency here—as Professor Jevons, commenting on their work, acknowledged—to define science as "work that is done by people recognised as scientists", which is tautological, although that is less true of their distinction between scientific and technical literature.

Dr Langrish meanwhile published an analysis of the abstracts and references used in the principal journal of industrial chemistry. He observed that whereas in recent years very little use was made of university research, the situation had been very different in the early days of the industry. In the earlier period, papers from academic sources were frequently cited: 62 per cent in 1884, falling to 27 per cent in 1899, and then more gradually, to 22 per cent in 1935, dropping to 5 per cent in 1952. Dr Langrish suggests that the technology associated with industrial chemistry quite rapidly became independent, producing its own research, with academic research becoming largely irrelevant to it.[33] Given the divergent objectives of the scientist and the technological research worker, once the original ideas had been well launched, the two moved apart, just as atomic physics and nuclear

[31] Gibbons, M. and Johnston, R., "The Roles of Science in Technological Innovation" *Research Policy*, III (November 1974), pp. 220–242.

[32] *Ibid*., p. 238.

[33] Langrish, J., "The Changing Relationship between Science and Technology", *Nature*, CCL (23 August, 1974), pp. 614–616.

engineering have moved apart. Again, the assumption is, that once you work in industry, you are no longer a scientist but belong to the technological profession.

Diffuse rather than Specific Connections between Science and Technology

Academic scientists and research workers in industry have often been trained together; it may be partly chance that directs a person to an academic rather than an industrial laboratory. Hence the great importance of education, the largest of Professor Jevons's three benefits—the training in techniques of experiment and investigation, the questioning, checking approach, and of course the simple knowledge of "properties, composition, and characteristics of materials or components" which accounts for 88 of the 300 external units of information and almost exactly the same proportion of the 887 studied by Gibbons and Johnston in 1974.

The handling of equipment is obviously one skill that is acquired in such an education. But is that really science or practical technology, if the technology is defined as the physical instruments, how to make them and how to use them? When used in basic research, it is still "hardware". Many of those famous applications of scientific discovery in the past arrived at their technological destinations as instruments, perhaps first devised to explore or demonstrate a theory, rather than through the theory itself. Marconi did not need Maxwell's theory; he did need the technique developed by Hertz, and the apparatus, which had already been made much more effective for emitting and receiving signals, by the efforts of Lodge and Branly. What Röntgen gave medical diagnosis was not a theory to fit X-rays into the spectrum of radiation but a new use for apparatus which utilised an improved version of an instrument designed by the laboratory technician Geissler.

Most of the cases studied in the two more recent investigations at Manchester were taken from chemistry. It could well be argued that chemical science has always been closer to technology than physics; it could be argued that chemistry deals less with the "fundamental principles of matter", and more with the more elaborate combinations of matter with which we normally come into contact. The investigation of biochemical, genetic or bacteriological enigmas has certainly led to "mega-innovations" in the past. Nevertheless, the crucial field from which major innovations have come in the past century has been physics.

Where could we fit some recent episodes? What, for instance, about lasers? Here the theoretical concept of inducing movement between quantum energy states to stimulate emission goes back some time, at least to the Second World War. Denis Gabor indeed claimed that "the laser was implicit in Einstein's equations of 1917".[34] Certainly, it emerged from the

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[34] Gabor, D., *Innovations: Scientific, Technological, and Social* (Oxford: Oxford University Press, 1970), p. 5.

apparently abstruse and fundamental world of quantum mechanics and stimulated emission of electromagnetic radiation. Through the 1940s and 1950s, various experiments were designed primarily to test theories about the effect of a fall from upper to lower energy states. The introduction of recent advances in spectroscopy suggested to Professor Charles Townes what became the maser; attempts to expand into the visible light region followed, and by the end of the 1950s the instruments for creating a laser had been constructed and demonstrated. Nevertheless, just as the idea of the laser was first published in the *Physics Review*, so it seemed for some years in the early 1960s to have been a scientific technique, which was in search of application.[35] Now the laser has become a focus of industrial activity, growing away from its parent in physics. It is not easy to assess the significance of either theory or the thought of potential applications on stimulating that growth. Holography might be another example of a technology which has grown out of scientific research, since although first conceived quite independently of laser technology, in fact it has been the child of the laser. Like X-rays, one of its main uses has been the detection of flaws in inaccessible places. Perhaps ultrasound would be another, similar case. The basic idea of very high frequency sound goes back to the 1870s; it was proposed by Rayleigh, who played a role in this particular tale parallel to Maxwell's. The theory of piezoelectricity worked out by Pierre Curie suggested a method: his former student, Paul Langevin, exploited these theoretical insights for acoustic searches for invisible objects, namely, submarines in the First World War. Other military and medical applications were tried with limited success. Real technological applications came only in the 1960s with the arrival on the scene of a professor of obstetrics who through chance connection had access to a firm specialising in the detection of flaws in industrial products; this was able to provide the engineers and the engineering to devise an instrument that could inspect a foetus in the womb, which avoided the dangers associated with older methods like X-rays.[36] Clearly, in all these cases more than one theoretical discovery underlay the technological development. But economic application still depends upon the eventual recognised need in a potential market—and upon the development of equipment by firms whose technologists have the past practical experience that can be invaluable in this novel context.

A symptom of the vagueness and uncertainty which quantitative studies like those of the Manchester school have not been able to overcome, is the taste for metaphor and personification. That is an entertaining study in itself. Professor Jevons's anonymous well-wisher comes from the science side—technology as the passive recipient of benefits. Professor Brooks toys with the image of science as the "seed", technology the "plant", but rejects

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[35] Torsaglieri, A. J. and Baker, W. O., "The Origins of the Laser", *Science*, CXCIX (10 March, 1978), pp. 1022–1026.

[36] Yoxen, E. J., "Technology, Images, Experience", paper presented to the British Society for the History of Science conference, New Perspectives in the History of Technology, March 1981.

that for technology the "seed", and science the "fertile field", because for him it is science that supplies the "healthy" environment in which technological ideas can be exploited rather than in fact being itself the origin of technological ideas. As any specific advance will depend on a considerable number of background events, scientific and technical, "one will usually find that many different strains of science were involved".[37] Gibbons and Johnston too see the science as a background environment; their metaphor is a pool of science, in which industrialists can fish "with greater or less success depending on their experience and expertise, and luck". The scientist, however, is by definition, swimming in the pool "and from this position he can draw the attention of fishermen to the location of the fish, or even present them with suitable specimens".[38] In consequence of their work, and its implications that science provides information, techniques and training, but does not very often initiate, Jevons changed his own metaphor for science to the "nursemaid" to invention; "she helps innovation to grow up—and moreover, she depends for her livelihood on making herself felt to be useful in that way. But she does not beget innovation, except very occasionally, illegitimately, under the back stairs".[39] Rather unusual in that technology appears as the master, science as the social inferior, the nanny who from time to time gets seduced by the master from her proper duties!

The view that science and technology are "distinct but related", separate and complementary, is also represented in such metaphors. Arnold Toynbee wrote that "physical science and industrialism may be conceived as a pair of dancers, both of whom know their steps and have an ear for the rhythm of the music"; first one leading, then the other.[40] Derek de Solla Price took this image as his text. He developed the theme of Lavoisier's plea for pure science by distinguishing between "papyrocentric" science—for science is published papers, and the scientist's property is his publications—and "papyrophobic" technology—for the technologist is keen to patent and then produce his artefact or process "without disclosing material that may be helpful to his peers and competitors before his claim . . . can be established".[41] Layton speaks of "mirror-image twins, two different communities each with its own goals and systems of values".[42] In practice, matters and persons may turn out to be more entangled. Donald Gould, who had been a doctoral student in Townes's laboratory at Columbia University when the latter published his idea and patented it, claimed that he had thought of the laser back in December 1957, and had his idea notarised, but had not been able to nourish it with the requisite diligence to make his claim good. Gould

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[37] Brooks, H., "The Interaction of Science and Technology: Another View", in Warner, A. W., Morse, D. and Eichner, A. (eds), *The Impact of Science on Technology* (New York and London: Columbia University Press, 1965), pp. 38–39.

[38] Gibbons, M. and Johnston, R., *op. cit.*, p. 241.

[39] Jevons, F. R., *op. cit.*, p. 737.

[40] Cited as epigraph: Price, D. J. de S., "Is Technology Historically Independent of Science? A Study in Statistical Historiography", *Technology and Culture*, VI (Fall 1965), pp. 553–558.

[41] *Ibid.*, p. 561.

[42] Layton, E. T., *op. cit.*, p. 565.

"had wanted to be an inventor, and perhaps because he saw himself as an inventor rather than a physicist, he neglected the scientific road to credit, which is to publish first".[43] However, Townes and Schawlow did not only publish first; they also filed for their patent first, some months before Gould.

Perhaps in the United States the utilitarian viewpoint was always stronger than in Europe.[44] The notion of "pure" science, motivated only by the aspiration to understand, has carried with it, at least in certain circles, an overtone of social and moral superiority to the profit-seeking activities of technologists. That was plain enough in Lavoisier's letter—however ill-advised in those circumstances—despite his insistence that "both are precious beings for the public weal".[45] Such an apparently aristocratic bias was bound to be unpopular in revolutionary France; it might be no less unpopular in practical, democratic America. Those who wished to defend basic science against disparagement as an activity carried on in an "ivory tower" probably had to do so more vigorously than did their European colleagues. In 1928 the physicist Robert Millikan delivered a lecture on "Michelson's Economic Value", i.e., the advantage which industry had drawn from the work of a scientist who had engaged in abstruse and fundamental research. For instance, he declared, "Einstein's equation and Aston's curve alone, the former due partially to Mr. Michelson . . . enable us to draw one definite and very important conclusion namely, *that there is no energy available to man through the disintegration of any of the common elements*". So, although such disintegration might be eventually possible, so much additional energy would have to be expended on the task that we must realise that "*there is no appreciable energy available to man through atomic disintegration*" [Millikan's italics]. Of course, some very heavy elements do disintegrate without our provoking them, but that is no help. "Radium, it is true, releases about a million times as much energy per gram in disintegrating as carbon does in burning, but there isn't enough of it, nor of any radioactive substance, to more than keep a few corner pop-corn men continuously going".[46] So Michelson saved industry the money that would have been wasted in the search for atomic power.

Utilitarian attitudes have also been prominent in Europe. Lord Rothchild's proposal that the support of research should centre on the "customer-client relationship" is in fact an argument that science merits support in so far as it is technology. If science demands such large funds, it must sooner or later try to pay its way. This view is not inconsistent with a

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[43] Wade, N., "Forgotten Inventor Emerges from Epic Patent Battle with Claims to Laser", *Science*, CXCVIII (28 October, 1977), pp. 379–381.

[44] There have been a number of conferences and seminars on this question, especially in the United States. See among others, Warner, A. W., Morse, D. and Eichner, A. (eds), *The Impact of Science and Technology* (New York: Columbia University Press, 1965); *Technology and Culture*, VI (Fall 1965), pp. 547–595; *Technology and Culture*, XVII (October 1976), pp. 619–742.

[45] Lavoisier, A. L., *op. cit.*

[46] Millikan, R. A., *Science and the New Civilization* (New York and London: Charles Scribner's, 1930), p. 163.

distinction between scientific and technological knowledge. Technological knowledge may, in some instances, be quite independent of scientific knowledge. But it is knowledge. Dr Layton defines this as the ability to design, a knowledge that is a "plastic geometrical, to some extent non-verbal mode of thought".[47] This may be placed alongside Dr Langrish's view that technology is not just "hardware", but "the concepts and knowledge which are embodied in the hardware".[48]

As Dr Layton wrote later, technology does not attempt the exactitude of scientific inquiry; the "world of engineering is not an ideal mathematical world at all".[49] This is correct, but the improvement of many technologies has depended on ever more exact quantified definition of problems of design, on ever more refined tolerances. It must be said at the same time that natural science does not always deal with an "ideal mathematical world". Perhaps that is simply an ideal.

Professor Hall has said that technology has been a "knowing how to", that is, how to achieve some purpose, or how to make something.[50] But that was not a knowing, a *scientia* in the sense used above. Now scientific technologies do indeed exist, they grew out of "knowing". Professor Hall accepts that scientific technology is not just the application of science. When he tries to define just what science has contributed to technology, he arrives at "1. mathematical analysis, extended from physical science to engineering; 2. the method of establishing facts by carefully controlled experiments; 3. the knowledge of relevant natural laws such as those of thermodynamics or genetics; 4. acquaintance with new natural phenomena such as electromagnetism or catalysis".[51] This is not too different from Dr Layton's view of the matter.

Indeed, Dr Layton does not think that his "mirror-image twins" are independent of one another, even though he perceives that technology was begotten of technology, not of science. However, he emphasises that by 1900 even those branches of engineering most directly derived from the old practical arts had taken on "the qualities of a science in their systematic organisation, their reliance on experiment, and in their development of mathematical theory".[52] When speaking of two communities of science and technology, he is aware that a good many individuals, including some of the most outstanding, straddle both. He seems to regret only that leading engineers and writers for the engineering profession have found it necessary to establish their status as scientists by publishing in physics. He thinks that,

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[47] Layton, E. T., "Technology as Knowledge", *Technology and Culture*, XV (January 1974), p. 36.

[48] Langrish, J, *et al.*, *op. cit.*, p. 43.

[49] Layton, E. T., "Scientific Technology, 1845–1900: The Hydraulic Turbine and the Origins of American Industrial Research", *Technology and Culture*, XX (January 1979), p. 89.

[50] Hall, A. R., "On Knowing How To . . .", *History of Technology: Third Annual Volume, 1978* (London: Mansell, 1978), pp. 91–104.

[51] *Ibid.*, p. 101.

[52] Layton, E. T., *op. cit.*, 1971, p. 568.

as a result, they have felt that their scientific objectivity would be tarnished if they were to acknowledge a social responsibility for the technology in which modern invention has brought into the world. Dr Langrish has also argued that the gap between science and technology will be reduced, when technologists again begin to read the scientific literature, in order to understand what they themselves are doing, now that their works so frequently affect the health and quality of life of their customers.

All agree that the comprehension of natural laws affects the growth of technology. Sometimes the relevant natural laws which Professor Hall mentions as his clause 3 may have been discovered a long time past, and so by the time of any specific invention in which they are drawn upon they may have become quite banal. If I were to try to design an electric banana peeler, the linkages from motor to blade could well have been in use since the Middle Ages, if not ancient Greece. The electric motor would now be standard, depending on a knowledge of electrodynamics laid down by the fathers of that science a century and a half ago. Professor Cardwell has made a distinction between "inventions which depend on a prior scientific knowledge" and those which "are substantially independent of science".[53] These latter include among more modern innovations, "barbed wire, zip fasteners, bicycles, sewing machines, etc.". They would seem to be equivalent to his subsequent definition of Watt's parallel motion as "a purely geometrical invention, quite independent of contemporary science", which embodies no principles unknown to Leonardo da Vinci, and indeed resembled some of Leonardo's ingenious notions.[54] Yet even the geometrical inventions of modern times have in practice depended on the prior development of metallurgy. A zip fastener could have been invented in the Renaissance, and would not have been more complicated than many of the decorative elements in the apparel of the rich. But the large-scale manufacture which led to the replacement of buttons, as buttons had replaced laces—that needed metal-working machines and alloys only available in our time, and the alloys at least in some measure came from an enhanced understanding of the structure of metals. Even geometrical inventions nowadays therefore embrace some if not all of Professor Hall's four categories. This qualifies but does not dissolve that distinction; even the inventions that make much more use of recent understanding of the structure of matter, like lasers, holography, ultrasonic scanners, are developed by technologists. Clearly, the two communities, scientific and technological, are far from exclusive. Professor Harvey Brooks has suggested that the scientist's and the inventor's intellects do not differ, so much as their emotional attitudes.[55] Hence many of the greatest physicists intended to be engineers, among them Einstein and Hertz. In wartime the

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[53] Cardwell, D. S. L., *Steam Power in the Eighteenth Century* (London: Sheed and Ward, 1963), p. 1.

[54] *Ibid.*, pp. 70–71.

[55] Brooks, H., *op. cit.*, pp. 39–40.

elite of physicists has twice in this century been diverted to military technology—not without grumbles, and an eagerness to return to "real" research as soon as possible, but all the same not without a fair degree of success.

Dr Reich offers the career of Irving Langmuir as a man who must belong to the chemists' community, on the ground that his contributions to fundamental physical chemistry were surpassed by few; but he worked all his life very cheerfully for General Electric and was always happy to stress the practicality of his scientific interests. He insisted on the need for sound theory in practical inquiries: a member of his team once remarked that "perhaps no piece of apparatus was ever built for the Bell system that was more practical than this theory. . . . latent in this were many, many inventions".[56] Much of his work started from problems that concerned the short life of existing light bulbs and their filaments, but to solve them he had to investigate in precise detail the physico-chemical environment within the bulb. That demanded a lengthy programme of research: "nearly all these experiments would have seemed quite useless or even foolish to a man making a direct and logical attack on the problem of improving tungsten lamps".[57] Now does a scientist who works in industry become thereby a member of the community of technologists? Vannevar Bush, whose *Science, the Endless Frontier* summarises what Dr Layton most dislikes about the old viewpoint, was not himself a basic scientist, more an ingenious Yankee technologist, an engineer with a command of physics and mathematics. His doctorate was in electrical engineering, and his first post at the Massachusetts Institute of Technology was as professor of power transmission. His differential analyser, a predecessor of later computers, could be regarded equally as science or technology—it was certainly "hardware" and it was meant originally for use in the electrical industry. Among his other inventions were a justifying typewriter, a survey-machine, and a "birdfeeder that discriminated against pigeons and bluejays".[58]

Most of the literature of this debate has concerned itself with the sociology of science and technology; what sorts of persons do what, and what need have they of one another to do it? A different procedure would be more philosophical; and one of the clearest of such philosophical studies of the distinction has been made by Mario Bunge.[59] Bunge looks for a difference in modes of discourse, rather than in attitudes or recruitment. He opposes scientific law to technological rule. Such rules are certainly only "grounded", "if and only if" they are "based on a set of law formulas capable of accounting for their effectiveness".[60] But a scientific law is a

[56] Reich, L. S., "Irving Langmuir and the Pursuit of Science and Technology in the Corporate Environment", *Technology and Culture*, XXIV (April 1983), p. 201, citing Southworth, George, *Forty Years of Radio Research* (New York: 1962), p. 73.

[57] *Ibid*., p. 210.

[58] "Obituary-Vannevar Bush", *Nature*, CCL (30 August, 1974), p. 804.

[59] Bunge, M., "Technology as Applied Science", *Technology and Culture*, VII (Summer 1966), pp. 329–347.

[60] *Ibid*., p. 339.

statement of what is the case, a statement of the truth, whereas technological rules are statements of what is effective in a certain situation. A law may be falsified, a technological rule can only be proved ineffective, but that is enough. Similarly Dr Bunge compares scientific prediction with technological forecasting. The scientific prediction has the form: "if x occurs at time t, then y will occur at time t′ with probability p": the latter, "if y is to be achieved at time t′ with probability p, then x should be done at time t".[61] The procedure of many scientific experiments, although they have an eventual law-like statement as their final objective, in the meantime have very much the form of a technological forecast. The technologist, then, is concerned with means and ends, not simply with relations, and if he does try to be objective, nevertheless "his ability consists in placing himself within the system concerned—at the head of it";[62] he remains partial and involved. Significantly, Dr Bunge extends this from the making of artefacts and the development of processes to the case of an applied geologist predicting a landslide in certain circumstances, and going on to forecast what needs to be done to avoid its worst consequences. Hence he provides his own refutation in a way that would not be possible in science, which merely describes the conditions in which earth movements take place. That allows for the same persons to be on both sides of the fence, which is necessary because the whole question is beset by the difficulty of establishing any definite outlines, any boundaries between categories. "Science" in English and "*science*" in French do not mean quite the same thing; it could almost be said that there is no exact and complete equivalence between the appropriate words in any two European languages, to go no further afield. Similar problems, if not worse ones, go with the various words for technology and "*Technik*" and "technique". Otto Mayr, at the Burndy Library conference, objected that the various metaphors used imply that science and technology are "two distinct entities that are opposite and mutually exclusive", in theory as separable as "black and white beans".[63] As he goes into the difficulties of any clear distinction, he decides that the only thing the historian can do, is investigate how this interaction or relationship was viewed in the past: "what previous eras and cultures have thought it to be".[64] However, if we do not know what it is now, and has been in the very recent past, are we not likely to find out only how confused the issue was in more distant times?

Concluding Observations

Attempts have been made to assess the contributions of science to the evolution of technology in quantitative terms. Their intention, or at least their hope, was to provide a "scientific" sociology of invention, with laws

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[61] *Ibid.*, p. 342.

[62] *Ibid.*, p. 342.

[63] Mayr, O., "The Science-Technology Relationship as a Historiographic Problem", *Technology and Culture*, XVII (October 1976), pp. 663–673.

[64] *Ibid.*, pp. 671–672.

that would underpin forecasts, and so suggest what should be done in order that a high level of science teaching and research in universities could be converted into a high level of qualified scientists and engineers. These in turn could be converted into a high level of productivity, innovation and profit in industry, and so increase each country's gross national product. So far these essays in constructing a model of the science–technology relationship have demolished a few old clichés. But they have not really put forward a satisfactory new model in their stead, only some neat metaphors. We still do not know the answers. Certainly, it is more difficult for commentators to remain objective, when they believe that wholehearted financial support for the science that is motivated primarily by intellectual interest might be affected if those who provide that support come to think that technology is not ultimately dependent on that kind of research, but independent of it.

However, that is not the whole story. Metaphors and sociological inquiries alike depend for their accuracy on precise boundaries. Here precise boundaries are just not available. This is why vivid metaphors have to take their place. Even to talk of genetic engineering, for example, is to employ a metaphor rather than a description. In most branches of medicine the practical art and the science are even more closely interwoven and in a variety of ways. The development of the general medical practitioner's stethoscope, for instance, required some knowledge of physiology and acoustics, but can we usefully make a comparison with ultrasonic scanning? So definitions all prove unsatisfactory and end in tautology. There are so many diverse sciences, and so many diverse technologies that no generalisation covers them all; the relationship between civil engineering and geology, is quite different from the relationship between chemical engineering and chemistry, or between nuclear physics and nuclear engineering. Plainly, most types of scientific endeavour need someone who has a practical skill in the manipulation of material and he is seldom the original theorist. Most technologies are created by individuals with a clear understanding of a wide range of scientific facts and their implications. To suppose, therefore, that one form of human activity is directly dependent on the other, still less its intellectual offspring, is not a sensible deduction from the immense variety of data.

So—has science created technology? The answer must be twofold. One answer is: No, it was not the prime originator, usually, not even the catalyst. The other is: Yes, modern technology would be impossible without scientific training and comprehension of the nature of things. Technology can and does carry on under its own steam. Technological achievements may not be intellectual in the sense that scientific theories are, but they are intellectual in their own way. As of old they require that sense of design, of the "go" of things, and of how to make things go, which they have inherited from the old pre-scientific crafts. What is known cannot easily become unknown again. But what is made can more easily be unmade.