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Engineering and Innovation in the Industrial Revolutions

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Abstract:

The ways in which engineers and engineering contributed to innovation during the major spurts of industrialisation are examined through a taxonomy of functions of the firm. The kinds of engineering required naturally interacted with the predominant fields for technological development, and in manufacturing until recent times this meant above all mechanical engineering. The objective of incremental innovation by mechanical engineers is defined as 'time-saving'. The training for this rather practical and process-oriented concern was chiefly practical, here considered as a 'knowledge' route to technological accumulation. All the major industrial revolutions considered here relied primarily on this during their industrialisation spurts. The alternative 'information' route through formal education developed more belatedly, and not always in the best interests of the economy at large. The main finding of the paper is that the economic success (and often social success) of engineers depended on how well they fitted into contemporary advances not just in technology but also in corporate organisation. Higher scientific qualifications for engineers were an unsuccessful strategy for Britain, though may prove more beneficial in the future.

1 Introduction

The precise contribution of engineers and engineering to industrialisation has not been seriously assessed by any scholar, and at present remains beyond our grasp. In this paper I intend to examine instead the ways in which engineers helped advance technology, and thereby provide a basis for rapid economic growth during the industrialisation spurts. I shall be contrasting the three great spurts: the first of which (the classic 'Industrial Revolution') began in Britain over two centuries ago; the second of which developed mostly in the USA over one century ago; and the third of which is currently unfolding, and is often seen as involving another geographical shift, this time to East Asia.[1] Specifically, I aim to look at the nature of learning in engineering, how this related to the needs of industrialisation in each 'industrial revolution', and how it related to organisational changes in the same periods.

Economists have long reflected on the nature of information, and more recently of learning. For the most part, this has been little more than brushing off any role for information, as in the orthodox theories of the firm and the supply side of economies, which begin with Assumption 1: the existence of 'perfect information'. With perfect information, one can go on to demonstrate the beauty of market forces and the efficacy of competition. In recent work it has become apparent that this assumption is generally unwarranted in any attempt to understand the real world. Rapidly developing branches of the subject such as the 'economics of information' thus consider such possibilities as misleading market signals, information that is asymmetrically distributed, and so on.

A different branch of the subject that has brought knowledge to the centre of things is the so-called 'new growth theory' and associated 'new trade theory', which blossomed in the USA from the mid-1980s, and is now at the heart of the agenda for industrial policy-making in many industrialised countries and regions. According to this theory, technology obtained

[1]This paper owes its origin to a presentation to the British Association, in Newcastle-upon-Tyne, in September 1995, in a discussion organised jointly by the Economics and History of Science sections of the BAAS, relating to Industrial Revolutions. I am grateful to all those attending for their comments.

through learning is in the nature of a free gift, over and above the usual processes of production (which on the side give rise to the new technology). In this manner, market forces and conventional economic models are compatible with economic growth, because growth stems from the bonus derived from new technology ('increasing returns').

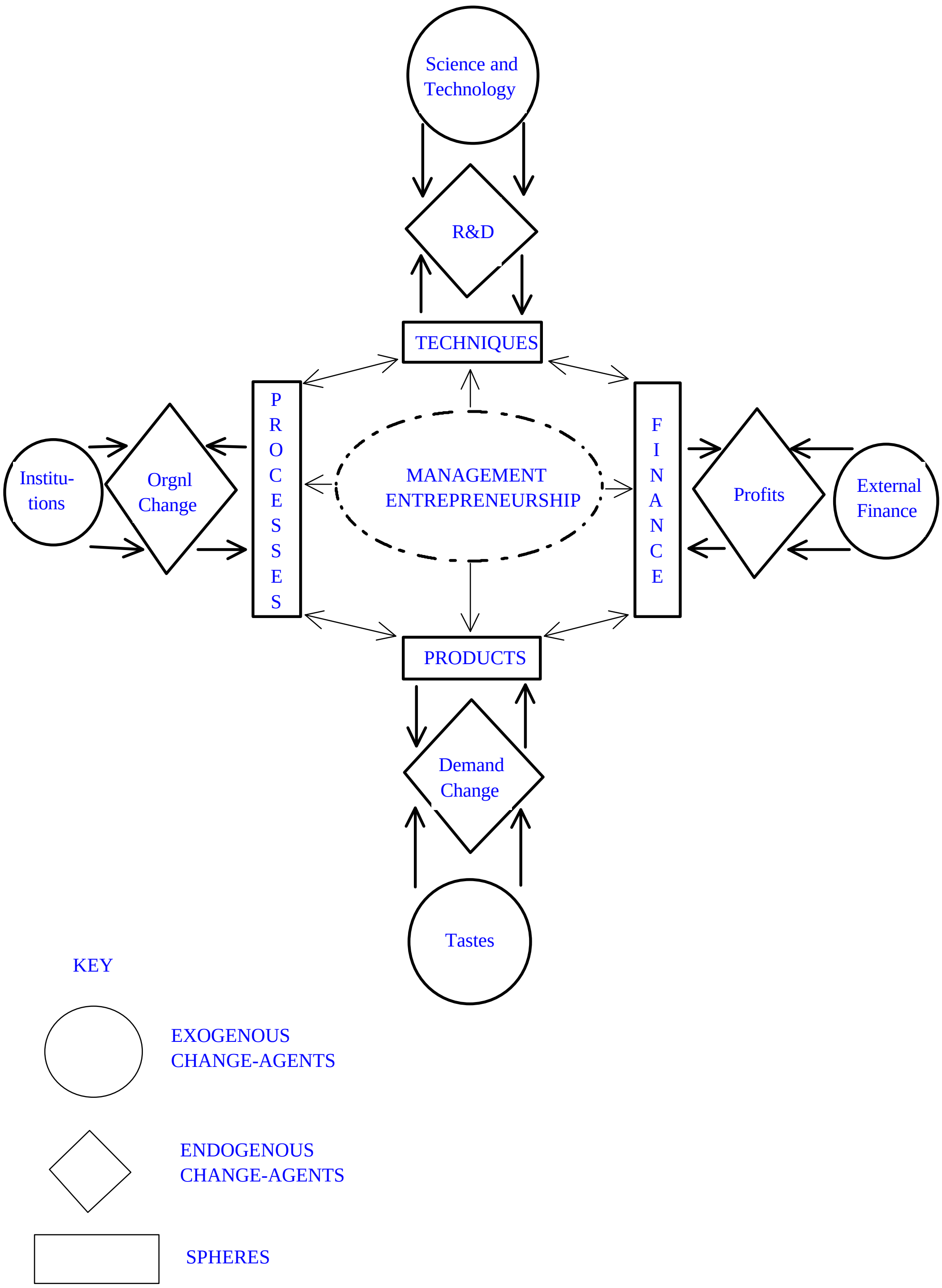
The present paper has some affinity with the latter approach. However in my view economists are still superficial in their notions of how new technology is generated. Surprisingly, they do little to assess the *cost* of bringing on technological change - the view just expressed that is a costless bonus has been undermined in the literature on 'technological accumulation', which shows just how many resources may need to be devoted to securing new technology (Bell and Pavitt, 1993). Secondly, they give inadequate thought to *what* precisely is learnt, through education, production experience, etc. Thirdly, they pay little attention to *where* learning takes place, except in yet other branches of the economics literature which examine the role of public vs private sector (in education and training). These three aspects, the latter two especially, are the main concerns of this paper.

We can usefully distinguish between the 'education' route to learning and the 'production' route. The former emphasises the provision of *information*, through means with which all readers will be very familiar. The individual accumulating knowledge distils his or her views depending on the quality of this information, but also on their previous learning, on to which this new information has to be mapped. The latter - learning obtained through experience, for example in production - places a more immediate emphasis upon the *knowledge*. The account of engineering to follow shows how different countries at different times have played up the information vs the knowledge avenues towards technological understanding and change.

The knowledge route requires some further consideration of where it takes place. Whereas information is supplied in educational institutions such as polytechnics, and disseminated through means such as books, periodicals, or computer networks, production experience is obtained in firms. The functions of the firm are set out schematically in Figure 1. Elsewhere I have tried to show that the four illustrated functions of technology, process, administration and product can in principle be parameterised two-dimensionally, to pinpoint the characteristics of any particular firm. Here it is sufficient to take a broader view. The firm has, in some recent literature, been regarded as a repository of knowledge (Fransman, 1994; Teece and Pisano, 1994). My own perspective is more precisely that firms exist in order to *transform* knowledge, and specifically to transform technologies into products. Technologies arrive at the firm structured according to the academic or similar training that its recruits have obtained, as physicists, biologists, etc. Firms need to convert the principles that can be derived from such academic training into products that are marketable, and which are structured according to industrial definitions - as electronic equipment, drugs, motor cars, etc. This involves both a cognitive transformation (some of which may already have been partly developed in applied sciences or technological-engineering coursework) and the development of the firm's other functions: the processes used to transform inputs into outputs, and the various administrative elements (finance department, legal department, and other managerial responsibilities).

It is the process sphere that I wish to highlight here. Though central to the application of engineering, etc, and indeed to the day-to-day operation of the firm, it has received little attention from economists, who devote their time principally to the other three functions. Sociologists do give some thought to 'labour process' - the ways in which the workforce is organised within firms to produce the output - but here my main preoccupation is with what Marx called 'capital process', ie the ways in which the plant and equipment itself is organised to produce output. I have argued that a predominant motive that has directed process innovation since the time of the First (British) Industrial Revolution has been *time-saving* technical change (von Tunzelmann, 1995b). Though it is an everyday commonplace to talk about saving time, it has escaped the consideration of economists, for whom time is not a 'factor of production'. Instead economists focus upon saving labour or other factor inputs

Figure 1: A micro-level taxonomy for production in the firm



(raw materials, capital, etc). In my view these are often not alternatives to saving time but consequences of saving time.

It was the engineers (defined as broadly as possible) whose function it was to achieve these savings of time. Such savings were reaped in four overlapping ways:

(i) through reducing downtime, ie periods during which the equipment was unable to operate;

(ii) through increasing throughput, ie rates at which the equipment handled the flow of output;

(iii) through improved machine co-ordination, ie getting various sub-components of the piece of equipment (machine, etc) to synchronise more efficiently;

(iv) through improved systemic co-ordination, ie getting all the major pieces of equipment and branches of the manufacture to synchronise more efficiently, as exemplified by the well-known interchanges between spinning and weaving innovations in cotton textiles or between smelting and refining in iron.

The gains achieved in these respects represented the 'normal' routine of the engineer, in terms of construction, operation, and innovation (Vincenti, 1990).[2] Specific examples for the classic case of British cotton textiles in the eighteenth and early nineteenth centuries can be given (von Tunzelmann).[3]

2 Engineering in the British Industrial Revolution

The supply of engineering talent available in Britain in the eighteenth century was not well-suited to developing 'radical' engineering advances. If we are to continue to see industrialisation as a radical departure from older norms, then Continental rivals were in a stronger position to launch industrialisation, so far as their resources of engineers were

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[2]'As defined in Chapter 1. It parallels the notion of 'normal science' as argued by T S Kuhn.
[3]*Op cit.*

concerned. The Germans in the sixteenth century, the Dutch in the seventeenth century, and the French in the eighteenth century, have perhaps the best claims to be regarded as being at the forefront of engineering expertise, each with impressive achievements to chalk up (Armytage, 1961). Britain was more likely to be importing this talent than exporting it.

For the most part, British achievements at this time owed to the seemingly more mundane level of 'normal' rather than 'radical' advance. Three kinds of factors promulgated the paradoxical advantages of 'normal' engineering and design. First of these was the nature of contemporary science. As is very well known, science had undergone a 'revolution' in the course of the seventeenth century, embodied most tangibly in the founding of the Royal Society in 1660 and the Académie Royale in 1666. Though both were founded with the Baconian intention of rendering science applicable to technology, their achievements in this regard were rather slight, and in the case of the Royal Society waned rapidly after the initial flush of enthusiasm. Science and technology were by and large separate worlds in the eighteenth century. In this sense, advances in science did not yet call for advanced technological backup. However science did contribute in two ways to the subsequent developments in technology: firstly through setting the example of 'experimental method' - the very core of the Scientific Revolution - as a means of analysis (but without having to communicate any of its explicit findings); secondly through its focus upon instrumentation and measurement.

The second supportive characteristic was the predominance of the small firm, typically run by an individual, family, or two-person partnership. Here the scope for large-scale engineering operations was very restricted, and the firm naturally concentrated upon its daily routines and how to better them.

The third factor lay in the nature of technological advance in this era. The emerging technological 'paradigm' for manufacturing industry was mechanisation. Nowadays machinery and technology are so closely interlinked that it is often hard to see that, in the early eighteenth century, it was far from obvious that machinery could provide the inevitable solutions to technological 'puzzles'. That it could do so owed most to its capacity for allowing time-saving in manufacturing processes. The most consistently successful way of attaining such time-saving was in getting the machinery to operate on a continuous basis, and the most straightforward way to do this was through supplying rotary motion. In contrast with the human body, where arms and feet worked best through to-and-fro motions, machinery was easiest to develop and improve by working through circular or cylindrical motions. However not all industrial processes could yet be converted to such operation, and a supplementary role for budding engineers - often a more demanding one - lay in improving discontinuous processes.

It needs emphasising that these general principles were by no means intuitively obvious, except perhaps with hindsight. The chemicals paradigm played a much smaller role in early industrialisation than the mechanisation paradigm, but where important it too contributed to substantial time-saving; nowhere more so than in the drastic reductions of time taken to bleach cloth using chlorine, etc. In non-manufacturing sectors, still other paradigms provided the standard solutions to production problems: in agriculture the advances were primarily biological (new crops, better rotations, improved breeding, etc), with mechanisation unimportant in Britain until the late nineteenth century; in mining they were energy based, resting above all on the invention of the stationary steam engine of Newcomen - probably the greatest technological feat of its age - and again with little mechanisation before the end of the nineteenth century. But in manufacturing mechanisation prevailed, and with it the role of the mechanical engineer.

A combination of skills was required to develop this machinery, and to improve it in accordance with the four characteristics of time-saving spelled out above. Three types may be given particular prominence. First were the smiths and others, accustomed to dealing with materials such as iron, from which the machinery was increasingly constructed. Second were the clockmakers and instrument-makers, who worked to make discontinuous movements approximate continuity, and were particularly important for reducing downtime from machine operation. But third and most relevant to the rise of engineering were the millwrights, who were accustomed to both rotary motion and systemic interdependence among the various items of equipment (power source, machine production line, etc). The words of one of Britain's most celebrated nineteenth-century engineers, Sir William Fairbairn, have often been quoted:

> ... [T]he millwright of the last century was an itinerant engineer and mechanic of high reputation. He could handle the axe, the hammer, and the plane with equal skill and precision; he could turn, bore or forge with the ease and despatch of one brought up to these trades; and he could set out and cut in the furrows of a millstone with an accuracy equal or superior to that of the miller himself... Generally, he was a fair arithmetician, knew something of geometry, levelling, and mensuration, and in some cases possessed a very competent knowledge of practical mathematics. He could calculate the velocities, strength, and power of machines, could draw in plan and section, and could construct buildings, conduits, or water-courses, in all the forms and under all the conditions required in his professional practice: he could build bridges, cut canals, and perform a variety of work now done by civil engineers (Fairbairn, 1861/3).

The crucial point here, even if one allows for a modicum of exaggeration, is the bringing together of complex knowledge into single individuals, in this case millwrights, and - despite the intellectual gifts that Fairbairn describes - based overwhelmingly on practical experience.

The early factories and mills could employ such millwrights and their successors, either on a one-off consultancy basis, or more permanently attached for overseeing and 'routine' innovation. In this respect, engineering remained essentially a matter of more or less isolated individuals, often autodidacts. Another strand however emerged in the early nineteenth century. This originated in the 'workshops' which, through applying Adam Smith's concept of the division of labour, came increasingly to dominate the production of machinery and machine tools (hitherto, textile machinery had been constructed in the textile mill itself). Such workshops introduced systematic production processes, and even embryonic assembly lines, to reap the productivity advantages of the division of labour. Secondly, they developed strong routines for learning, dominated by pupilage and apprenticeship systems. The leading workshop of Henry Maudslay in the early nineteenth century produced pupils such as Richard Roberts, subsequent inventor of the self-acting cotton mule, and James Nasmyth, subsequent inventor of the steam hammer, both of whom had in the meantime established their own businesses. Until about 1850, almost all British mechanics had trained as apprentices.

The notion of the mechanic was itself becoming differentiated, even polarised, along class lines becoming omnipresent in British industry at large. Left out of the story of heroic individuals were the artizans and 'mere' mechanics, ie the skilled workers responsible for day-to-day equipment operation and maintenance. In the 1820s and 1830s especially, there was a rush of middle-class enthusiasm for more formal and scientific education of these groups (Berg, 1980). Mechanics' Institutes or similar were set up in many towns, and periodicals such as the *Mechanics' Magazine* (from 1823) flourished. Around 700 of what Carlyle dubbed the 'steam-intellect societies' existed ca 1840. But they disappeared with almost equal rapidity around the middle of the century, for reasons that are somewhat obscure, but presumably have most to do with growing class antipathy (fears of Chartism, etc) and rising trade-union activity from skilled workers on the shopfloor. By and large, though some survived in rather altered form (like Birkbeck College), the 'information' route to knowledge acquisition by skilled mechanics and technicians was merely a temporary digression from the predominance of the 'knowledge' route of apprenticeship and practical experience.

The same, however, could be said of their social superiors, in the guise of the 'heroic' engineer-entrepreneurs. Pupilage in the workshops of Maudslay, Nasmyth, etc was expensive - figures of £500 to £1000 were commonly quoted, and were large sums by the standards of the day - but remained preponderant for qualifying as a mechanical engineer. The successful then left to set up their own small workshops, and the tradition of the small enterprise continued. These were noted for their independence and particularly their hostility to government intervention. They were equally hostile to trade-union activity of their employees, and to the threat of an inrush of women (from telephony, etc) in the latter nineteenth century - before World War I only the Society of Aeronautical Engineers (founded rather bizarrely in 1866) permitted women as full members (in 1898) (Buchanan, 1989, p122).

This independent spirit manifested itself in an intense desire towards self-regulation - mechanical and other engineers regarded themselves as best fitted to assess their own standards and qualifications for their jobs. The framework in which this would be conducted was the professional association. The pattern was created by the establishment of the Institution of Civil Engineers in 1818. In view of the functions engineers saw themselves as being called upon to undertake, and in the light of the function of transforming knowledge that I have stressed for the firm, it is worth quoting the assessment of one of the founders (H R Palmer) in that year:

> An engineer is a mediator between the philosopher and the working mechanic, and, like an interpreter between two foreigners, must understand the language of both... Hence the absolute necessity of his possessing both practical and theoretical knowledge.[4]

In this bridging role, the predominant part was to be played by the practical rather than the theoretical. The Institution of Civil Engineers duly wrote similar sentiments into their preambles. They were followed by the Institution of Mechanical Engineers (1847) and a host of other institutions and societies that were set up as the demands placed on engineers themselves became fragmented and subject to division of labour. The institutions offered some prospect of maintaining distance from the hoi-polloi of working mechanics and of asserting pretensions to gentility in Victorian society, but the engineers found it difficult to

[4]Quoted by Armytage, *op cit*, pp122-123.

have their professional status accepted by wider society. In Victorian Britain, and still to a large extent today, the public at large seemed often oblivious to the distinction between professional engineer and skilled technician.

One solution that became more popular late in the nineteenth century as the structure of professional institutions fragmented was to raise the scientific content of engineering expertise; in due course this was to lead towards not just university degree qualifications for engineers, but qualifications which placed considerable stress on the scientific overtones of engineering. Universities had for some time sought to invade the field of professional training for engineers, by setting up courses that would stress the academic as well as the vocational side of the field. The high cost of pupilage encouraged universities to offer lower-cost routes to qualifications. A few of these courses survived beyond the middle of the century, such as that at UCL in London, but most lapsed, not least because professional societies often required university graduates to undergo further pupilage in workshops after their university degree, thus doubling rather than cutting the training costs. More generally, the university courses were unsure of whether their instruction should emphasise academic material - the 'information' route to learning - and if so, how. The solutions were slowly forged by some gifted professors after 1850, notably W J MacQuorn Rankine at Glasgow and the polymathic Fleeming Jenkin at Edinburgh. These saw the need to bring the then recent findings in fields like thermodynamics to the less-academic, through writing introductory textbooks and establishing balanced courses. Essentially the British 'compromise' was to graft university education on to the existing system of pupilage, and accept that the latter would for some time continue to be the main source of training. Near the end of the century, the professional institutions began more consistently to see academic standing as an offset to their failing attempts to secure social standing, and first introduced formal examinations and other means besides practical experience for professional accreditation.

3 Engineering in British industrial 'decline'

While such 'entry barriers' into the profession of engineering steadily rose during the twentieth century, its social status rose much less assuredly. Sociologist commentators have indeed argued that the quest for scientific credentials was misguided (Glover and Kelly, 1987).[5] Their main point is that the bulk of work undertaken by trained professional engineers was not in any degree scientific. In practice, about three-fifths see themselves nowadays in their employment as managers rather than as specialists; while next to none of their training - at least until very recently - would have broached these crucial managerial functions. The responsibility here lay not just with the university courses but more extensively with the professional associations themselves, which for so long had set their face against commercial criteria. For the most part, the nineteenth-century institutions, and their twentieth-century descendants, opposed managerial as well as technical involvement of their members, and for reasons that are somewhat harder to fathom.[6] With a growing emphasis on science and rejection of management, engineering graduates plumped for specialised work in R&D and design rather than for production work. The sociologists mentioned above kept coming across allusions to 'dirty production' and 'sordid sales'. The R&D/design work tended to remain distanced from production and marketing, even within firms, with negative effects on the necessary association of technological knowledge and product knowledge described at the beginning of this paper.

Not only did the social status of the engineers themselves thus fail to benefit greatly from this pattern of events, nor really did the commercial status of the country. For reasons already given, it is extremely difficult to give any reasonable evaluation of the cost to the country of an inadequate engineering contribution, and if one were to speculate on the basis of other such assessments one would be inclined to say that the cost was fairly small - certainly relative to the loss of economic power to newly emerging industrial rivals such as the USA or Germany.

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[5]For example. and sources quoted therein.

[6]There were some exceptions, of course; for instance in gas engineering where managers' associations and engineers' associations had much greater interaction.

But the loss was symptomatic of what was occurring more broadly in British industrial production. Engineers were by force of circumstance finding themselves in the eye of the transformative function of firms as outlined above, but without full cognisance of what this might entail, and certainly without the managerial power that the situation warranted. The power 'vacuum' remained filled instead by the skilled workmen, or their foremen. There are many historians who now consider that the basic British failing was in management, and specifically in its inability to wrest control of production processes from the shopfloor (Lazonick, 1990).

Within the engineering profession, the influential Finniston Report of 1980 ('Engineering Our Future') coined the term *the engineering dimension* 'to convey the interaction of engineering with non-engineering factors in determining manufacturing performance, and to emphasise the importance of considering the whole manufacturing system and not just aspects of it ...' (Finniston).[7] This integrative role, which parallels the notions of firm function suggested by Figure 1 above, was then spelled out through international comparisons:

> Major features of a successful engineering dimension, less well-established in Britain than elsewhere, involved the financing and realisation of technological innovations; the co-ordination of policies to inform and support industry's response to market changes; and the management and organisation of the engineering aspects of manufacturing. In each respect we found deficiencies in this country compared with our competitors, who have shown greater understanding and recognition of the essential role of engineering and engineers within their industrial cultures... [T]here is no cultural equivalent in Britain, and hence no basis for according similar esteem, to the European concepts conveyed in German by 'Technik' - *the synthesis of knowledge from many disciplines to devise technical and economic solutions to practical problems*. This 'third culture' (alongside science and art), which underlies the concept of the

[7]Chairman; original in italics.

> engineering dimension, is well understood in Continental Europe, in Japan and the a lesser extent in the USA ...[8]

How British engineering came to be overtaken may be further assessed by comparing with the first of these major industrial rivals, the USA.

4 Engineering in US industrialisation

The origins of American engineering were in fact astonishingly similar to those in the UK - 'astonishing' in the sense that there was practically no communication across the Atlantic to act as a direct impetus, at the time the American profession was first taking shape. Initially there was virtually no academic basis for engineering - unlike in say eighteenth-century France.[9] Engineers came from the same two types of background as in Great Britain, namely millwrights who were itinerant at first but later came to be employed, usually alone, in mills, and especially the workshop trainees. The workshops remained fairly small, but continued to produce leaders of subsequent generations of American engineering who had set up their own businesses after serving their time as trainees. The operative mechanics lived at a different level, but were favoured (if that is the right word) with similar outpourings of periodical literature and educational provision to their equivalents in Britain. This period of enthusiasm waxed and waned at almost the same time on the two sides of the Atlantic.

Above the operatives, the aspiring leaders of US engineering found themselves embroiled in clashes between what has been called 'shop culture' and 'school culture' in the late nineteenth and early twentieth centuries (Calvert, 1967). Shop culture emanated from the workshops and stressed practical experience, school culture arose in colleges and universities and gave a more academic twist to engineering training. So far the stories of the two countries read as virtually identical, though there have been surprisingly few attempts to draw explicit comparisons.

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[8] *Ibid*, 26; my italics.

[9] The only significant exception was the Rensselaer Polytechnic Institute in the state of New York, for civil engineering from 1824.

The differences which emerged in the later nineteenth century owed less to internal factors within the engineering profession than to external factors associated with broader industrial and corporate change. To explain these, let us go back to Figure 1. The rising industrial might of the USA in the second half of the nineteenth century was not built in the first instance on any major changes in technology. To be sure, new technological paradigms such as electricity, organic chemicals and the automobile were in the offing, but US industry was fairly well established before they stole the scene. US industrialisation patterns departed from those in Britain in the other three functional spheres.

For reasons to do with the structure of American household incomes and taste patterns, ie for demand-side reasons, American consumers wanted rather standard, undifferentiated but reliable goods - very different from the class-divided structure of British demand. American firms thus concentrated on producing a very limited range of products, which were differentiated from those produced by rivals by way of aggressive marketing. Production processes aimed at producing these homogeneous goods as quickly and cheaply as possible, aiming to benefit from economies of scale from large throughputs. Process efficiency in these standardised products was raised through designing 'interchangeable parts', initially for weapons in the early nineteenth century, and later for a wide range of consumer durables (Hounshell, 1984). To take advantage of these scale economies, and to cover the large geographical area of the United States, large companies arose - first in railroads and by the 1880s in manufacturing (Chandler, 1977).

Despite the similarity of its origins, American engineering evolved during the latter part of the century to meet these different organisational and market needs. Professional societies arose in partial imitation of their British counterparts, though somewhat belatedly - the Mechanical Engineers not until 1880 (in fact the ASME did not become a proper professional association until 1908). The leading periodicals, with titles like *The American Machinist*, suggested less antipathy to getting hands dirty in production than was the case in Britain. Above all, mechanical engineering saw its position as oriented to business and to selling, rather than to professional abstention. The elite emerging from the leading workshops always stressed their objectives in the marketplace.

One aspect of this orientation to selling was their concern with costs. A common American definition of the engineer was 'Someone who can build for a dollar what any old fool can build for two dollars'. Alternatively this was expressed by H R Towne, at Purdue University in 1905, as 'The dollar is the last term in every engineering equation.'[10] Early sociologists and economists interpreting the rise of capitalism came to the conclusion that, at least in the USA, its primary characteristic was 'rational cost accounting' (Weber, 1927; Clark, 1923). One route to such rationality was through standardisation and interchangeable parts, and here engineers were to the fore. The workshop of William Sellers was instrumental in producing de facto standards for screw threads and dozens of similar components, in the middle of the nineteenth century. In the manner already described, Sellers' shop produced equally influential pupils such as George Corliss, of the American steam engine, and Frederick Winslow Taylor, of scientific management. A primary function of engineers was to ease what the economist-sociologist Thorstein Veblen called the 'interstitial adjustments' that arose in the course of every production chain, and Veblen repeatedly stressed the role of standardisation towards this objective (Veblen, 1964). In other words, engineers sorted out the immediate time-saving problems of excessive downtime and low throughput, but more broadly the problems of machine co-ordination and system co-ordination that arose as production processes became increasingly complex.

Taylor's short book, *The Principles of Scientific Management* was of outstanding importance in publicising these issues (Taylor, 1911). After his workshop training, Taylor had contributed significantly to innovation in high-speed metallurgy, but it is for his management views that he is remembered. Taylor believed that all production operations could be reduced to 'scientific' principles relating efficiency to time, even such mundane processes as shovelling. Time-and-

[10]Quoted by Calvert, *op cit*, p225.

motion studies and similar procedures for evaluating how scientific was management followed from these principles. Taylor has earned much obloquy, both at the time and subsequently, for opening the door to the 'deskilling' of labour, through reducing work to its lowest common denominator. Actually, Taylor himself espoused the opposite principle of 'enskilling' labour by raising skills as far as possible, instead of cutting them to as little as possible. Historians and sociologists still vigorously debate what the actual outcome was.

Clearly the amount of 'science' involved in scientific management was not very high; though Taylor assumed it was rising all the time, as technology became more scientific. The main point was that entrepreneurs needed to maintain control of production processes, in contrast with the British pattern observed above, of entrusting workplace control to the foreman or gang leader - and for this they needed considerable understanding of the production technologies themselves.

The message here was not lost on the alternative approach to engineering training, which was the 'information' route through formal educational qualifications. From the 1860s, greater impact was being made in formal courses than experienced in England (Scotland was in better shape), through creating institutions such as the Massachusetts Institute of Technology and Cornell University. This has often been attributed to the Morrell Act of 1862, which permitted grants of federal land to support colleges, and from which both MIT and Cornell benefited. However it was not until the later 1880s that mechanical engineering courses really began to prosper. This 'school culture', as Calvert terms it, deliberately aimed at average-to-good students rather than at producing geniuses. The curriculum was likely to be broad-ranging, in the manner now familiar from American undergraduate courses. A survey of US engineering schools in 1892 showed 40% requiring English history in their course structure, 48% English literature, 49% geography, 80% American history, 82% algebra, and so on (Calvert).[11]

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[11]*Op cit*, chap 4.

This quite different strategy from the British attempt to upgrade the scientific content of engineering had a distinct purpose in mind, which was to fit its graduands to the kinds of jobs they were likely to obtain. 'School culture' and 'shop culture', though rivalrous in many ways, were agreed upon the importance of business and of selling. The colleges saw themselves as a route into business for those of lower social standing than the star pupils of the workshops, allowing their students to substitute education for social class as their means to occupational mobility. A survey of 650 graduates over the years 1871 to 1895, conducted by the *American Machinist* in 1896, showed to the author's satisfaction that, 'These statistics suggest that college-trained engineers from eastern schools were becoming less inclined to enter situations in which they themselves would be entrepreneurs and were more likely to enter relatively large, bureaucratic corporations where their titles were specified as mechanical engineer ...'[12] The schools were educating people not for the top strata but for middle and lower-middle levels within the firms.

School culture thus gained ground over shop culture in the USA because it geared itself better to the contemporaneous changes in business organisation, towards the giant enterprise and hierarchical management. The contrast with Britain was also stark. Essentially, the task of American engineers was to make mass production work. The 'interstitial adjustments' required to permit high-volume throughput in industries such as metal-working were extremely complex by the standards of the time (Chandler).[13] What was called for was a redesign of the whole production system to save time and other resources as effectively as possible. The introduction of electricity as the emerging basis of industrial energy at first added to these complications. In an elegant analysis, Devine has shown how power in the factory evolved from the steam-engine paradigm of a centralised power source, distributing power to every part of the factory through a web of shafts and belts, to the electric-motor paradigm of power sources attached to every single machine, with the power networked internally by simple cables and switches, and externally hooked up to some centralised

[12]Quoted by Calvert, *op cit*, p151.
[13]*Op cit*, chap 8.

generator many miles away (Devine, 1983). This process took some forty or so years to accomplish (roughly 1880-1920), but even so the USA achieved this new production system more rapidly than its industrial rivals in the Old World. US engineers may have been less scientifically trained than their European counterparts, but they were more successful in developing new production systems in keeping with broader corporate and technological changes.

With the system as a whole in mind, the new US giants in electrical engineering, dominated by General Electric and Westinghouse, required their engineering trainees at the beginning of the twentieth century to rotate jobs around the factory, to gain experience in its widening range of activities: six months in the draughting room, six months in the testing department, six months in the manufacturing division, and so on (Calvert).[14] Almost all these electrical engineers were salaried employees, not executives. Based on experiences attained in the new industrial laboratories, such as that at GE, R&D work tried to balance the scientific content of advanced research against the company's needs of improved methods and products (Wise, 1985; Reich, 1985). 'Information' and 'knowledge' both had to be allocated their function in the firm.

5 Engineering in Japanese industrialisation

American industry bestrode the world for the first two-thirds of the twentieth century, based on its systemic strengths as outlined above. Some time after about the late 1960s it, too, however entered a more painful era. Productivity growth markedly slackened, and macroeconomic disturbances became more frequent and more serious. Many causes have been suggested for this new retardation, and the more macro-oriented factors cannot be examined here. But problems also arose at the micro level of individual enterprises. The usual suspects at this level relate mainly to financial and managerial shortcomings, associated

[14]*Op cit*, pp74-75.

with the growing power of financial concerns (von Tunzelmann, 1995a).[15] Here I wish to link these to problems associated with production processes.

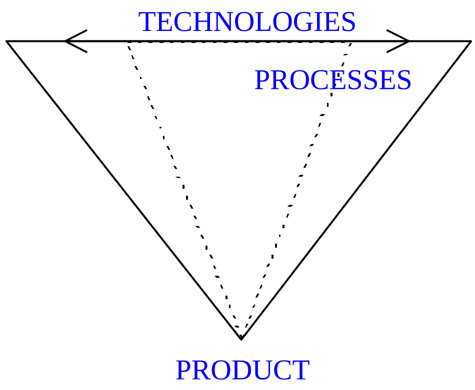
The difficulties on this score were exacerbated by broader trends in technological and market development. In Figure 2, the top panel shows schematically that a greater and greater range of technologies were becoming embodied in each individual product - think of a modern motor car or computer, and the range of technologies it embodies, and think further of the areas of frontier research relating to these products, which span an ever-broadening range of scientific disciplines. The bottom panel shows that, conversely, major new technologies were going into an ever-widening range of products - think for instance of the semiconductor. The period therefore witnessed the growth of firms that were not just selling multiple products, but having to incorporate multiple technologies to develop and produce these multiple products.

The large American corporation, dating from the late nineteenth century, efficiently solved the problem of producing multiple products. It did so by developing the *multidivisional* system of management, in which each product area was developed rather autonomously by distinct product divisions, while the range of products was overseen by a smallish central office, responsible for broad strategic issues (Chandler, 1990). Each product division included its own functions relating to technology (R&D), production and marketing, etc. This worked quite well, so long as the technologies, marketing, etc, of each product did not overlap with those of the other divisions. But in a world of increasing complexity, with multiple relationships between technologies and products as illustrated in Figure 2, such overlaps became significant. Here the multidivisional system, with its separation of R&D departments within firms, could not work so well, and indeed many present-day high-tech companies are trying to evolve alternatives.

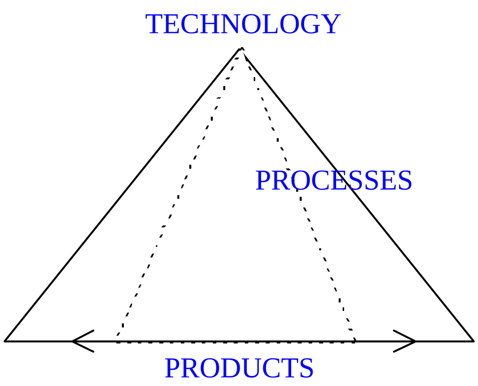
[15]These arguments are summarised in chap 8.

Figure 2: The entrepreneurial problem of scope and scale in the late 20th Century

1. Many more technologies to produce a single product



2. Many more products produced from a given technology



The Japanese production system developed a more robust way of dealing with these kinds of complexity. Engineers play a more potent part in Japanese as compared with American manufacturing. To do so, the engineering function has developed rather differently from that in the USA.

Its origins lie in the training and educational patterns that emerged early on in Japanese industrialisation. On the one side, there was a strong tradition of indigenous mechanical knowhow, based on traditions (known as *karakuri*) that dated back well before modernisation (Odagiri and Goto, 1993). Toyoda, the founder of the Toyota chain of companies, was one such *karakuri* master, and it was through these means that he developed ingenious methods of reducing downtime, etc that in due course became the foundation of the Toyota production line. Here there are strong parallels with the West.

On the other side stood the nascent educational approach. This was effectively introduced in a polytechnic set up in Tokyo in 1873, with its first principal being a Scotsman called Henry Dyer. Dyer combined the experiences he himself had found variously in the German *technische hochschulen*, the French *grandes écoles*, and his native Scottish institutions, influenced by Rankine and Jenkin as described above (Morikawa, 1991). To these, Dyer added the element of practical in-course training for his engineer pupils, requiring them during their degree to undertake two years of secondment, in say government mines and factories. By contrast, American engineering schools of the time, for all their worldly orientation, rarely ever attempted to provide external experience. Private industry in Japan - for example the Mitsubishi Nagasaki shipyard - also found itself having to provide its own practical training, because of deficiencies in the secondary school system (Fukasaku, 1992). Dyer's polytechnic eventually became the engineering department of the new Tokyo University (1886). Because Japanese universities were being set up around the late 1880s, by which time engineering was beginning to become acceptable in western universities, engineering never suffered the same lack of status in Japanese universities as compared with the latter.

Nevertheless, financial interests remained dominant in early Japanese industrialisation. Ronald Dore has shown that it took the upheaval of defeat in the Second World War to dislodge the financial powers and bring a new generation of engineers to industrial predominance (Dore, 1973).[16] Financial interests re-established themselves in Japan in the later 1980s, with results that appear to have been disastrous for the Japanese economy.

From my perspective, the important point was the particular strength of *production engineering*. Whereas production engineering has always been a minute part of the British

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[16]Also his recent unpublished research.

engineering scene (Glover and Kelly),[17] it dominated the picture in Japan. The Japanese system of manufactures embodied such production and process engineering in all its best-known characteristics: just-in-time production, lean production, total quality control, etc. All of these aimed to save time (and often space) in the context of process efficiency.

In the environment portrayed by Figure 2, of multiple technologies and multiple products, this worked more effectively than the hierarchical American system. Its basis lay in 'horizontal decision-making', which meant leaving as many decisions as possible to the production worker on the shopfloor (Aoki, 1986). The ability of workers to react to production problems in real time not only speeded up throughput, but provided the focus for meeting and resolving new production problems - this was the dynamic gain from just-in-time and total quality control (Schonberger, 1982). It also permitted the introduction of 'lean management', as many middle tiers of management could be swept away (it is interesting to contrast this with the recent British vogue for establishing more and more tiers of middle management, eg, in the National Health Service). To do this of course required workers that were highly skilled. In the Japanese factory, such workers had to be multiskilled, and able to comprehend the whole range of tasks undertaken in the factory (Carmichael and MacLeod, 1993). Skilled workers were often hired on more or less lifetime tenure by their companies, but required to rotate around jobs throughout that working lifetime. R&D people thus obtained experience in production, marketing, etc, and conversely. Instead of the divorce between R&D or design and production all too common in Britain and the USA, R&D was structured according to what the company produced, and not according to the particular scientific training that these employees might earlier have received (Westney, 1993).

The problems encountered by many American companies were thereby resolved. Functional divisions were broken down by mobility within the factory. Variety of products was achieved by their engineers developing production processes that permitted rapid transfer to producing

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[17] *Op cit*, chap 6, note that in 1982/3 some 9342 students began engineering courses in Britain, only about one-fifth of the number in Japan. Of that British number, just 155 were assigned to production engineering courses. By comparison, there were, say, 635 entering to study classics.

new products ('one-touch set-up', 'single-minute exchange of dies', worker-controlled reprogramming, etc). By comparison with the rigid American assembly line introduced by Henry Ford, the Japanese assembly line, as for example in Toyota, allowed virtually instant shifting to new variants of the basic product, in accordance with shifts in consumer demand.

There were limitations to this strategy, however. The 'knowledge' route to advance depends heavily on the relevance of past learning and technological accumulation. If the new technologies in question are such that past experience is of little guidance, then this can be outflanked by the 'information' route, accessing more quickly the new modes of thinking. That is, when the primary need is for *radical* changes in science, engineering and technology, rather than 'normal' progress, the balance of advantage may tilt. The American system, based on external rather than internal mobility - mobility of people between companies and between types of institution, creation of new companies, etc - may be superior in such respects. The Japanese have been notoriously slower at developing new scientific fields such as biotechnology. To change direction, the Japanese system has to rely on a more painstaking procedure of extending existing strengths within its companies, as Miyazaki has shown for the case of optoelectronics (Miyazaki, 1995). Although success in industrialisation has in the past been associated with an emphasis on the 'knowledge' route through engineering and the like, the position is now rather delicately poised. It seems likely that success in the future will go to those who are able to devise the best combination of 'information' and 'knowledge' and apply it to economic growth.

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