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Technology systems and technology policy in an evolutionary framework

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The central purpose of this paper is to outline an evolutionary theory of technology policy and to connect it with the emerging literature on national systems of innovation. Any understanding of technology policy must be based on a clear understanding of the nature of technology and the important differences between science and technology. Technology can be treated in terms of knowledge, skills and artifacts and in each case there are different variety-generating mechanisms, different selection processes and different institutional structures. For policy purposes, the degree of connection between these different dimensions of technology is at the core of technology policy.

In this paper I propose to sketch some general aspects of an emerging evolutionary perspective on technology policy. This perspective has developed out of the wide range of literature on innovation summarised by Freeman (1994) and I do not propose to go over this ground again. Rather, I shall draw out some of the themes which lead to the evolutionary perspective and to a concern with the institutional context of innovative activity. I do not have space for details of policy and the reader is referred to the relevant literature (Tisdel, 1981; Rothwell, 1986; Nelson, 1992A; OECD, 1992; Tassey, 1992). Suffice it to say that policies and policy frameworks differ across countries and vary within countries over time. Indeed, the relation of policy frameworks to wider cultural and historical conditions remains a much under-investigated topic.

The paper falls into three parts. The first compares and contrasts market failure and evolutionary perspectives on innovation, leading to a distinction between the optimising and the adaptive policy-maker. The second section introduces recent themes in the accumulation of technological capability, of which the ideas surrounding technology paradigms and technology systems are of particular importance. The final section concludes with an application of these ideas to the concept of a national innovation system.

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1. Old and new in the policy economics of innovation

Market failure

We cannot avoid making some brief initial comments on the traditional welfare economic foundations of technology policy and the contrasting evaluation frameworks provided by the established equilibrium and recent evolutionary approaches to technological change. Left to itself, will a market economy allocate the appropriate volume of resources to the generation and application of new technology? This is the traditional question. In the equilibrium view the starting point is the proposition that states of perfectly competitive equilibrium are characterised by market prices which measure the marginal valuations of inputs and outputs attributable to individuals as consumers, producers and suppliers of production inputs. Such perfectly competitive states support Pareto-efficient allocation of resources in which the welfare of any one individual cannot be enhanced without diminishing the welfare of at least one other individual.

Much of the traditional economic theory of technology policy is concerned with the so-called 'market failures' which prevent the attainment of Pareto equilibria by violating one or other of the conditions for perfect competition (Hall 1986; Wolf, 1986; Stoneman, 1987). The most important of these violations are related to missing or distorted markets. Put briefly, future markets for contingent claims in an uncertain world do not exist in any sense sufficiently for individuals to trade risks in an optimal fashion and establish prices which support the appropriate marginal conditions. Because the appropriate price structure is missing, distortions abound and the policy problem is to identify and correct those distortions. Missing markets imply constrained efficiency and constrained effects of policy intervention. Moreover, missing markets imply the need for agents to form expectations on the likely private values of their actions, expectations which policy can certainly influence. In such cases the question naturally arises of whether non-market processes–direct bargaining or political activity, for example—should be promoted to improve resource allocation (Newbery, 1990). Since the development of technology is uncertain and future oriented it is certainly susceptible to these missing market distortions. The innovation process both generates and is influenced by uncertainty and this aspect of market failure is particularly damaging to the possibility of a Pareto-efficient allocation of resources to invention and innovation. The difficulty is deeply embedded in the nature of technical knowledge, the creation of which depends upon the establishment of information asymmetries (Dosi, 1988). In a quite fundamental sense, innovations and information asymmetries are one and the same phenomenon. Indeed, such asymmetries can scarcely be termed market imperfections when they are necessary conditions for any technical change to occur in a market economy. As Stiglitz (1991) makes clear, the resulting unequal distribution of knowledge creates multiple problems of adverse selection and moral hazard which in turn deny the possibility of Pareto-optimal market processes. Notice that this involves much more than a trade-off between dynamic and static efficiency. Rather it is saying that innovation and information asymmetries are inseparable and thus innovation and Pareto-optimality are fundamentally incompatible.

While problems of asymmetric information are at the heart of technology policy, other aspects of market failure are also relevant. Appropriation externalities have always been recognised as a major constraint on the incentives to innovate, as reflected in the fact that the patent system is one of the longest established instruments of technology policy. Patents are the institutional device whereby market economies seek to cope with the peculiarities of knowledge production. They limit appropriability at the cost of creating temporary monopoly rights in exploitation. Similarly, the public good attributes of scientific and technological knowledge imply that market solutions to the allocation of resources to innovation will not be efficient. Finally, the indivisibilities inherent in the innovation process imply that there are increasing returns to the exploitation of technology and that it will be necessary for firms to retain some market power if they are to recover the costs of innovation. At best, an innovating industry can be monopolistically competitive, and from this different angle, Pareto-efficiency and innovation are seen to be incompatible (Dasgupta and Stiglitz, 1980; Dixit, 1988).

While the case for technology policy as a corrective to market failure is well established, one needs to recognise that government interventions can fail as well (Krueger, 1991). For a variety of reasons, imperfect information, the separation between those who benefit and those who pay, bureaucratic capture, pressure group activity, and political myopia, governments may undertake mistaken interventions (Eads and Nelson, 1971; Henderson, 1971; Wolf, 1987). It does not automatically follow that government policy will be welfare-improving. This is particularly so with respect to innovative activities, the formulation of which entails access to detailed microeconomic and social information. Indeed, it has long been recognised that the strength of a market economy *vis-à-vis* a centrally planned economy is precisely the efficiency and flexibility of the former in terms of the decentralised and distributed gathering, storing and communicating of detailed information (Nelson and Winter, 1982; Nelson, 1987).

The evolutionary perspective

At this point we turn to the evolutionary approach to technical change and the implications for policy. Firmly rooted in the behavioural theory of the firm, its focus is upon decision rules, learning capabilities and adaptive behaviour, and the interactions between these behaviours and various economic selection mechanisms (Nelson and Winter, 1982). The central policy issue that it prompts is the contrast between efficiency and the innovative creativity of firms. Creativity is intimately connected to uncertainty and the discovery processes by which firms find and exploit their own choice sets. Whether it is because of organisation, the individuals involved or historical happenstance, no two firms are expected to innovate in identical fashion and it is this emphasis on the decentralised emergence of technological diversity that is a defining characteristic of the evolutionary approach.

While there are a number of evolutionary approaches (Witt, 1991; Hodgson, 1993), they have in common a fundamental concern with processes of economic change. In assessing the contribution which they can make to technology policy, it is vital to understand the ways in which they jointly represent a change in perspective from the equilibrium viewpoint. For present purposes, evolutionary economics can be reduced to two central concerns, namely the processes which determine the range of available innovations, and the processes which alter the relative contributions which different innovations make to economic welfare. The fundamental issues are dynamic and intimately connected to a quite different view of competition from that deployed in equilibrium theory. Moreover, change is not to be interpreted as response to exogenous changes in data but rather as change which occurs endogenously without reference to adjustment to some equilibrium state. This entails a shift from perceiving competition in terms of price to viewing competition in terms of those decisive cost and quality advantages which arise from innovative behaviour. It entails a shift from perceiving competition in terms of states of equilibrium characterised by different market structures, to competition as a process of change premised on the existence of the differential behaviour of firms and other economic agents (Downie, 1958; Nelson and Winter, 1982; Metcalfe and Gibbons, 1989). It is only with this process perspective that the role of entrepreneurial behaviour becomes intelligible, since an equilibrium theory cannot, as a matter of logic, determine the rewards to entrepreneurship which are necessarily transitional. It is only in the process perspective that many competitive behaviours of firms are explicable, behaviours which from an equilibrium perspective are typically interpreted as anti-competitive market imperfections. Indeed, it is central to the evolutionary perspective that economic progress is only possible in what, from an equilibrium viewpoint, is an inefficient world. It is not in the least surprising, therefore, that scholars concerned to understand historical patterns of technical change have begun to develop evolutionary theory (Mokyr, 1990, 1991). Equally, it is not surprising that, together with concepts of individual equilibrium, they have abandoned optimisation as the route to explaining individual behaviour and replaced it by adaptive learning and the creation of novelty. It is by this change in approach that attention is switched to the strategic, cognitive and organisational aspects of firms to explain why they behave differently.

A central purpose of policy now becomes that of stimulating the technological innovative capabilities of the economic system: enhancing the learning processes in firms and other institutions to generate variety in behaviour. The focus of attention ceases to be market failure *per se* and instead becomes the enhancement of competitive performance and the promotion of structural change (Mowery and Rosenberg, 1989). Evolutionary policy is fundamentally tied up with the creativity of firms and supporting institutions, and arguably, there is no more powerful source of differential behaviour than that provided by technological innovation. This granted, the problem in understanding reduces to the economic significance of diverse behaviour and here the distinctive feature of evolutionary theory is its intrinsic capacity to make sense of variety. Once this step is taken, one can immediately recognise that evolutionary economic processes are essentially open ended and unpredictable. As Austrian and other subjectivist economists are fond of emphasising, there is an irreducible element of discovery in the working of the market process (Hayek, 1948; Buchanan and Vanberg, 1991). Nonetheless, although the emergence of novelty is unpredictable, the processes which translate novelty into coherent patterns of change are not, and it is on this distinction that the role of technology policy hinges. There is nothing unscientific about this: science is much more than prediction, certainly a historical science such as the economics of technological change (Gould, 1990). The temptation to view these developments as an illegal 'epistemological transfer' from biology to economics is easily dismissed: biology is simply one of many applications of that particular mode of thinking which defines evolutionary analysis. It has no claim to be the only evolutionary science. Whether biology or mechanics provides the appropriate background for economic thinking is not a question that it is fruitful to pursue here.

For present purposes, evolution means two things: the gradual unfolding of phenomena in a cumulative and thus path-dependent way; and, quite separately, a dynamics of system behaviour which creates change and emerging structure from variety in behaviour. From the technology policy viewpoint, change is to be interpreted in three different and interdependent ways: the emergence of genuine novelties in the form of new design configurations; the internal development of existing design configurations through sequences of innovations; and the comparative diffusion of competing alternatives in a market environment. Two of the immediate consequences of this are that it is natural to see innovation and diffusion as inseparable processes, and that technological change and structural economic change go hand in hand. There is nothing further from the evolutionary argument than the belief that technological progress can be understood as if it were an aggregate process of balanced growth. It follows that traditionally two questions have defined the scope of evolutionary analysis: the origin of variety and the nature of selection. In biology the answer to the first question is found in the concept of blind variation, that is, variation which is independent of selective advantage (Campbell, 1987). In economics, this obviously is not the whole story: while no treatment of innovation can ignore a stochastic element, it is also true that innovation represents guided and intentional variation (Hodgson, 1991) purposely undertaken in the pursuit of competitive advantage. Economic agents learn from experience and anticipate future states of the selective environment in a way quite unknown in biological or ecological selection. Naturally, this greatly enriches the scope of the theory. Indeed, as Nelson has repeatedly stressed, it is this guided element in innovation which explains the rapid and sustained rates of progress in capitalist market economies. The concept of a selective environment also requires careful handling. In the simplest cases, it can be equated with a market mechanism within which users and suppliers interact in traditional fashion. However, this represents only one level and mode of selection. Any framework in which agents interact in order to choose between competing patterns of behaviour has selective properties. In particular, organisations create their own internal selection environments to choose between competing alternative futures and their associated patterns of behaviour. As the discussion below of innovation systems indicates, the degree of matching between choices made at different levels of technological selection exerts a strong influence on patterns of technological change. Beyond the traditional two questions, a third must also be raised, that of the outcomes of selection processes feeding back into the subsequent generation of variety—indeed this aspect is crucial to a full understanding of the evolutionary dynamic. All selection processes absorb the available variety, and if evolutionary change is to continue, variety must be continually recreated by some other mechanism. Two issues are important here: the role of inertia and institutional limits in setting bounds to the generation of variety; and positive feedback mechanisms which link the generation of variety to the exploitation of increasing returns and endogenous innovation, that is, link it back to the selection process. That one can have a theory of variety generation is too far fetched: it is not possible to treat novelty as if it were an analytical concept and it is certainly not possible to anticipate the emergence of novelty. However, one can make considerable progress in identifying important feedbacks which keep a balance between variety generation and variety dissemination.

At this point we sense that a clear framework for policy analysis is emerging which distinguishes policies which influence variety generation from politics which influence selection processes. As far as variety generation is concerned, one of the major contributions of the evolutionary school has been its insistence that the pattern of technological innovation depends on much more than the behaviour of individual firms. This leads us directly to the idea of technology systems and national systems of innovation. Similarly, the treatment of selection processes leads us to the treatment of technological competition and the diffusion of innovations. In this paper we focus attention on the first of these.

Optimising and adaptive policy making

It is perhaps useful to approach the issue of technology policy with the help of three distinctions. First, we have a distinction familiar to all scholars in this field between the generation of technology and its application, akin to the equally familiar but treacherous distinction between innovation and the diffusion of innovation. Second, one can distinguish policies which assume that the innovative capabilities of firms are given from those which seek to enhance these innovative capabilities. Third, and more important, is a distinction between optimising and adaptive approaches to policy making.

Equilibrium economic theory provides the leading example of the optimising approach. Here the problem of technology policy appears as the identification and adoption of superior economic equilibria, defined in terms of an appropriate economic surplus criterion. Left to itself, the market mechanism will generally fail to produce the best possible allocation of resources to the development and application of technology: the source of the inefficiency rests in inappropriate incentive mechanisms or in an imperfect distribution of information across economic agents. Firms always do the best they can but, for whatever reasons, the constraints they face are the wrong ones. To change incentives becomes the central policy concern, a way of thinking best summarised as the theory of the optimising policy maker. Such a policy maker seeks to maximise social welfare in the context of individual agents who seek to maximise their personal welfare, where social and private welfare being out of step, defines the arena of policy choice. The favourite metaphor here is of the policy maker as a fully informed social planner who can identify and implement optima. While market failure virtually defines the equilibrium approach to policy making, the very ubiquity of market failure in an innovative economy limits its practical insights and limits its role to providing a general policy rationale. Theory predicts that firms may spend too little or too much on innovation, generate those innovations too early or too late, and generate innovations which are too similar or too different. The nature of the policy advice therefore depends on the specifics of each case.

Evolutionary approaches are less developed but clear lines of differentiation with the equilibrium approach have already been established. The fundamental difference is the displacement of equilibrium and optimisation as the organising concepts. As outlined above, evolutionary theory is concerned with why the world changes endogenously, with the way in which technological competition is the driving force behind structural change and economic development. Process and change, not equilibrium and state are its central concerns. Imperfect information is an integral part of this process; indeed, the development of privileged information is the mainspring of profit opportunity in a capitalist market system. To paraphrase G. B. Richardson (1960), knowledge which is available to everybody provides a profit opportunity to nobody. The central policy problem becomes that of increasing the probability and the profitability of experimental behaviour. Thus, the attention of the evolutionary policy maker shifts away from efficiency towards creativity, and patterns of adaptation to market stimuli and technological opportunity (Smith, 1991). In fact, the policy problem becomes one of confronting the evolutionary paradox that competitive selection consumes its own fuel, destroying the very variety which drives economic change. To maintain economic change, the conditions must be set in place to regenerate the requisite degree of variety: it is upon this that the continuation of economic progress depends (Beer, 1985). This is not likely to be best pursued in terms of a policy of 'picking national winners', an approach which smacks too much of the optimising policy maker, when in practice technological challenges are rarely well defined enough to make rational calculation possible. In fact, the adaptive, evolutionary policy maker is far more concerned to influence process than to impose predetermined outcomes, far more concerned to enhance the adaptive, learning capabilities of firms. Within this framework it is not individual innovations that are the focus of attention but rather the conditions which draw forth a sequence of innovations from a particular design configuration in a process which is strongly shaped by the related diffusion processes. Technology policy should focus on co-evolving technological and market environments, not upon individual innovations.

In short, our claim is that the evolutionary policy maker adapts rather than optimises, and his/her central concern is the innovation process, the operation of the set of institutions within which technological capabilities are accumulated. The canonical policy problem is defined in terms of the dynamics of innovation in a world characterised by immense micro complexity (Allen, 1988). Moreover, just as individuals operate under the constraints of localised, imperfect and uncertain information, so too does the adaptive policy maker. There can be no presumption that the policy maker has a superior understanding of market circumstances or technological information; rather what s/he does enjoy is superior coordinating ability across a diverse range of institutions. Technology policies can fail just as easily as the technology strategies of firms and the issue is how well policy makers learn and adapt in the light of experience. Options are politically and administratively constrained, policy makers have objectives other than the general welfare, and one cannot expect the policies which emerge to be independent of the processes by which they are formed. There is also the question of policy delivery, how a policy is to interact with the agents it seeks to influence. Many routes are often available to deliver a given policy to its intended recipients but little is known as yet about their relative advantages. For example, a framework which requires firms to compete against each other for support will produce different outcomes from a policy of support which is available to all who are willing to join the queue for public support. Despite the differences between the equilibrium and evolutionary viewpoints, they work with the same salient features of the economic system. These are three in number: the opportunities to innovate, the incentives to innovate and the distribution of the resources to innovate. With these three pillars of policy the evolutionary and equilibrium theorists share common ground but draw different conclusions. In the following we shall focus primarily on questions of opportunity.

2. The accumulation of technological capability

Any discussion of innovative capabilities assumes a relationship between the amount of effort devoted to innovation and the resulting innovative outputs. Indeed, without some regularity between innovative input and output, an innovation possibility frontier, there is little for the policy maker or the company strategist to relate to. Not surprisingly, this is how most formal thinking on innovation proceeds (Machlup, 1962; Nordhaus, 1969; Dasgupta and Stiglitz, 1980A; Gort and Wall, 1986). For any given state of knowledge it is expected that greater innovative effort results in greater innovative output, and it is this expectation which motivates the resources firms allocate to innovation and the way in which the process is organised in R&D laboratories. Not surprisingly, such a formulation raises a number of difficult questions relating to the units in which inputs and outputs can and should be measured, and with respect to the inherent uncertainty surrounding the innovation process. A range of case studies from many different sectors have made it clear that technological accumulation is not random; rather, technologies develop in a structured fashion within frameworks which, at least with the benefit of hindsight, appear well defined (Sahal, 1981; Dosi, 1982; Pavitt, 1987; Zuscovitch, 1986; Dosi and Orsenigo, 1988). Central to this perspective on technological change is an emphasis on learning processes. In an obvious sense all knowledge acquisition involves learning, but it is clear that many distinct kinds of learning can be distinguished. As Malerba (1992) has emphasised, learning phenomena have a number of attributes in relation to technological change: learning is costly and occurs in different parts of the firm; it involves the interaction between internal and external sources of knowledge; it is cumulative; and it supports localised and primarily incremental innovation. Indeed, a crucial aspect of the innovation process lies in the exchanges of information which take place between the developers and the users of new technology. Malerba distinguishes six categories of learning activity which we may re-group together into three broad categories: learning which is a joint product of activities producing and using artefacts—the famous categories of learning by doing (Arrow, 1962) and learning by using (Rosenberg, 1982; learning which involves the interaction with external sources of knowledge located in other institutions, whether other firms as suppliers or customers, or science and technology agencies; and internal, directed learning which is typically organised around a formal R&D programme. Malerba convincingly argues that the different kinds of learning activity are productive of different kinds of technological change, so that firms with different learning structures will generate different patterns of innovation. This diversity in sources of innovation experiments is central to the evolutionary approach to technical change. Notice that not all learning activity is carried out through formal R&D programmes, even though policy is often focused on this dimension. Hence policy to support technology should address the diversity of learning mechanisms and the conditions which enhance the learning capabilities of firms, and should reflect the fact that successful innovation requires learning about markets and user needs as well as learning about technology.

At least four further attributes of the innovation process must be stressed (Dosi and Orsenigo, 1988). First, and more so than is the case with a conventional input/output relationship, innovation possibilities are anticipated relationships in the minds of technologists and research managers, relating an investment in innovative effort to an expected technological improvement. Obviously, different individuals in different organisational contexts will anticipate the possibilities with different degrees of imagination and accuracy, and this is a major element in explaining the variety in innovative performance across firms. How such technological expectations are formed is a legitimate policy concern. Second, and following directly, the relations between input and output are subject to considerable uncertainty; indeed, the unforeseen and unintended consequences of innovation programmes are central to the history of technical progress. In many cases we have uncertainty proper where no probability calculus can be applied; the experiments are one-off, they change the conditions for the next experiment and it is never possible to enumerate completely the set of possible outcomes. However, in those cases where the potential range of innovative outcomes can be listed, it is possible to apply probability calculus and interpret the innovation possibility frontier as some average of a stochastic process. Many approaches can be followed to introduce risk: making the probability of discovery an increasing function of innovative effort (Loury, 1979; Dasgupta and Stiglitz, 1980B; Reinganum, 1989); applying the theory of order statistics to define the expectation of improved performance as a function of innovative effort (Evenson and Kislev, 1975; Nelson, 1982); or, as in much recent evolutionary theory, using Markov theory to define the probabilities with which innovations take place and the probability distribution of improvements (Dosi *et al.*, 1993; Winter, 1986; Nelson and Winter, 1982). For the policy maker, uncertainty is a fundamental issue, for there can be no guarantee of the pay-offs from any programme to improve technology: failures will be mixed with successes in a no doubt politically disconcerting fashion. Third, the relationships between input and output take as given the current state of the art. However, the consequence of devoting resources to innovation is to change the state of the art, and so redefine the innovation possibilities for the next period. New knowledge and enhanced skills are typically joint products with the improved artefacts which define innovative outputs. In this regard, Machlup (1962) has made a very useful distinction between those innovative activities which are agenda enhancing and those which are agenda reducing. The former increase the productivity of future innovative effort, by identifying new innovation possibilities, while the latter reduce future possibilities. Thus over time, innovation possibilities systematically shift the very meaning of the cumulativeness of technical change, with a presumption that within any one technology the pattern of change is ultimately agenda reducing as the long-term limits on improvement are reached (Kuznets, 1954; Gort and Wall, 1986).

Fourth, the innovative possibility frontiers are not only technology-specific, they are also firm-specific (Pavitt, 1990; Nelson 1992B). The productivity of the innovative process is very much an organisational issue, depending on the individuals involved and the way in which their creative endeavours are organised and connected with the rest of the firm. Some firms are weak, some are strong at innovation, and those which are strong at one stage in their history may subsequently wane in creativity. What is at stake here is the capability of the firm as an innovating institution: the opportunities it perceives; the incentives to which it reacts; the resources it can marshall; and its ability to integrate and manage the R&D process in relation to other activities in the firm. On all these aspects there is a rich literature and it is clear that the field of innovation is one of the best areas in which to observe the inherent variety which surrounds any creative activity. Much depends on the management of research and development and, although this cannot be our concern here, we can note the significance of practices such as parallel R&D programmes in determining R&D productivity (Arditi and Levy, 1980; Nelson, 1961).

The notion that innovation possibilities are firm-specific and vary systematically over time is also at the core of the rich product cycle literature on technological change (Abernathy, 1978; Utterback, 1979; Majumdar, 1982). Product cycle analysis identifies typical stages in the development of design configurations: a fluid early stage with many competing alternatives leading finally to a stage of technological maturity, and an innovation pattern in which an initial focus on product innovation is replaced by an increasing focus on process innovation. While not all technologies fit this pattern (Pavitt and Rothwell, 1976), there are a substantial number of innovations where the regularities in innovation and patterns of industry development are remarkably consistent. Indeed, the technology cycle appears to be matched by an industry cycle of dynamic adjustments in output levels and growth rates, with an initial increase in the number of firms followed by a sharp decline to a stable level (Klepper and Grady, 1990; Klepper, 1992). All this, of course, is strongly reminiscent of the retardation theories of industrial dynamics first presented in the 1930s (Burns, 1935; Kuznets, 1954).

Dimensions of technology

Any understanding of technology policy must obviously be based on a clear understanding of the nature of technology, and, in particular, of the important differences and inter-relations between science and technology. It is usual to define technology as the ability to carry out productive transformations. It is an ability to act, a competence to perform, translating materials, energy and information in one set of states into another, more highly valued set of states. For present purposes it is vital to distinguish technology as three interdependent forms (Layton, 1974): as knowledge, as skills and as artefacts. In principle, policies can be designed to influence each of these aspects of technology independently, although in most circumstances all three elements are jointly produced. The artefacts dimension, products and their methods of production, 'technique' as it is often called, is the central concern of firms which develop new and improved artefacts in the search for competitive advantage. The skills and knowledge necessary to underpin technique are also the concern of firms but they are also produced by a much wider set of institutions. In fact, the central fact about the modern process of innovation is that it is based on a division of labour, as Adam Smith clearly foresaw when he wrote about the role of philosophers and men of speculation. Division of labour produces efficiency gains from specialisation and professionalisation but it also requires a framework to connect together the component contributions of different agents. As far as knowledge and skills are concerned this aspect of connectivity, or technology transfer, cannot be effectively co-ordinated by conventional markets, for reasons explained above. As we shall see, the connectivity of technology-producing institutions should be a central concern of technology policy.

The technological division of labour is reflected in the many different kinds and branches of knowledge which are relevant to the innovation process. Technology is much more than science and innovation involves much more than technology. These different types of knowledge are not only produced in specialised institutions; they are also accumulated by different mechanisms. No satisfactory classification of knowledge for innovation has yet been produced, although several important distinctions are often made (Vincenti, 1990). Fundamental, basic or pure knowledge is distinguished from applied and engineering knowledge, as in the Frascati definitions, a distinction based on the nature of the knowledge. Fundamental knowledge is usually defined in terms of 'laws' of natural phenomena and their empirical verification by replicable, experimental methods. Applied knowledge is more specifically focused on particular generic productive transformations and may or may not be capable of verification by scientific means. A further distinction which is made is that between curiosity-based knowledge and mission-based knowledge, a distinction related to the motivations behind the process of knowledge accumulation. Since the communication of knowledge is such a central element in the innovation process, a further classification in terms of the codifiability of knowledge is of considerable importance. All knowledge is transmitted in a codified form, as Arrow has emphasised (1969, 1974). However, the code may be more or less explicit and this is the basis for distinguishing codifiable from tacit knowledge. The fundamental point is that different kinds of knowledge are associated with different costs of writing and subsequently translating technological codes. These encoding and decoding costs are fixed outlays relative to the use of the information, and when average fixed costs are high it is not likely to prove economic to transfer knowledge in a codified form. It is not the case that knowledge once produced is freely available to all who demand access to it. There are significant reception costs as well as transmission costs:

on this distinction rest many of the connectivity problems within national technology systems. Codified knowledge embedded in journals and books is the standard method of communication in science; coding is economic because widespread dissemination is intrinsic to science. However, even codified statements involve some tacit elements which are not readily expressible in language, as with the individual skills of a scientist which contribute to the detailed method of an experiment. At the other limit we have purely tacit information which cannot be transmitted at all, being inseparable from the individual in which it is embodied. This is what is often meant by pure skill or pure genius: it cannot readily be replicated by anyone else. Now much of the knowledge which defines a technology lies between the extremes of the purely codifiable and the purely tacit. In science the method of accumulation is through an experimental research programme, with the design of the experiment guided by established law-like relationships. It is central to the notion of validity in science that the results of experiments be replicable by other scientists and for this they must be codifiable in considerable detail. By contrast, a research programme in engineering science may lack the benefit of a precise scientific understanding of the relevant laws. The process of knowledge accumulation is primarily empirical, as trial after trial yields a gradual improvement in understanding (Vincenti, 1990). Even in strongly science-based industries such as pharmaceuticals, paints and pesticides, the primary mode of technology accumulation is *via* empirical development (Pavitt, 1987). In fact, a great many important technological transformations take place with only the vaguest scientific understanding of the details of why they work. From the humble automotive battery to the dynamics of combustion in an engine the contribution of scientific knowledge only provides a general background to understanding. As the tacit component of knowledge increases, the significance of learning by observation and induction also increases. Accumulation is more *via* experience and communication is increasingly verbal and through personal contact. In this way the accumulation of tacit knowledge is intrinsically connected to learning by doing and by using, that is, it is linked inextricably to specified activities carried out by specific organisations.

Paradigms and systems

Recent work on technological change has brought these various considerations together under the twin themes of technology paradigms and technology systems. Dosi (1982) was the first to articulate the concept of a technology paradigm. The point is not that the idea of a scientific paradigm can be carried over more or less exactly to the study of technology but rather that any paradigm provides shared cognitive frameworks for the individuals and institutions seeking to advance the technology. In this it provides a framework to identify opportunities and a set of constraints on the kinds of technical improvement which can be considered. In short, a technology paradigm is a device for dealing with the tyranny of combinatorial explosion. If we think of a technology as a set of design concepts integrated together to form a design configuration, the force of this point can be made immediately. With n possible design concepts there are $2^n - (n+1)$ possible integrated technologies, an impossibly large number for n as small as 100. What paradigms do is to abstract from this set of all possible concept combinations the much smaller subset which have been discovered and demonstrated to be workable. Once a workable design configuration has been established, it provides a framework within which technologists can define problems and identify solutions: it becomes the framework for incremental artefact improvement within a stable broad knowledge and skill base. Rather than being random, technological development is guided in such a way as to reduce the rate of mutational error. From this it is a short step to characterising paths of advance as trajectories (Dosi, 1982) or as innovation avenues (Sahal, 1985) or as dominant designs (Abernathy, 1978; Utterback and Suarez, 1993). Each label captures the idea of canalised or creodic development, that is, change within constrained opportunities. An excellent account of these issues has been provided in a study of the engineering of the Britannia railway bridge by Rosenberg and Vincenti (1985). They summarise the emergence of the chosen design configuration for the bridge in these terms: 'In a broader and more general sense, the engineers learned something perhaps more important. By struggling with their problem and forming conceptual models, they learned to think synthetically about the design of an important class of wrought iron structures. This *intellectual framework* [emphasis added] enabled them to combine empirical data, theoretical understanding, and artful surmise—each limited and incomplete—to attain their practical goal' (pp. 30–4) This is a splendid example of the exemplary properties of a technological paradigm and its role in guiding the development of technology. We would simply add here the further insight that in setting up learning mechanisms to exploit specific technological opportunities, organisations inevitably develop a degree of commitment to the required mode of learning and it is this commitment to a specific learning structure and associated competencies which helps explain their inability to adapt to the emergence of new design configurations based on different knowledge paradigms. Hence they have great difficulty in adapting to the change in the set of technological possibilities and in many cases are forced out of the industry (Cooper and Schendal, 1976; Starbuck, 1983; Abernathy and Clark, 1985; Zuscovitch, 1986).

The second modern theme is the systemic properties of a technology. This occurs most obviously at the artefact level but equally it applies to the underlying design principles and their interaction. Thus, Henderson and Clark have usefully distinguished between technical change in the components of a system and technical change in terms of the system architecture, the way these components interact. This leads them to a fourfold innovation taxonomy which fruitfully expands the usual distinction between incremental and radical change. For present purposes, however, the significance of a system perspective is its implications for the guided nature of technical change. Compatibility between components and balance in their performance capabilities provides a binding constraint on the development of the system as a whole. To make the most of improvements in one component or sub-system, it is necessary to improve complementary elements and in some cases engage in a thorough re-design of the systems architecture. Several authors have drawn attention to this phenomenon as a guide to learning effects: Rosenberg writes of imbalances and focusing devices, Sahal of technological guideposts, and Hughes of reverse salients. Each of these concepts is based on a systemic view of technology and the opportunities and pressures which shape innovative activity. We shall note here that the systems perspective provides a hierarchy of levels at which change can occur, as system divides into sub-systems and components in repeated fashion, so that radical change at one level can equally be interpreted as incremental change at higher levels. For the same reason that systems shape opportunities to learn, they also place interrelatedness constraints on what might be achieved. An improvement in one sub-system can only be adopted if the costs of engineering compatibility with the rest of the system keep the overall portfolio of changes economically feasible.

The significance of all this for policy is that any programme of technical development draws on different kinds of knowledge created in different institutions and accumulated by different mechanisms. The integration of the relevant information and the variety in modes of acquisition is the crucial aspect. A scientific research programme is different from an engineering research programme and both differ from a process of technical development for a particular artefact. Timescales of 'experiments', methods of acquiring knowledge and the objectives of the process are simply different. Technology policies need to be sensitive to the different sources of knowledge and the different motivations and methods which underpin its acquisition.

However, it should not be overlooked that innovation involves much more than the accumulation of technological knowledge. Schumpeter (1911), it will be remembered, argued that innovation and invention are quite independent phenomena, that the creation of technology and the application of technology are different economic functions. Teece (1986) has drawn attention to how innovation in firms depends on their command of important complementary assets to translate new technology into innovation, the absence of which may thwart success. A wealth of research has established that a detailed knowledge of customer needs is crucial to the innovation process, a fact that partly explains the poor results of major government civilian technology programmes which failed to take this into account. Innovation studies have also made it abundantly clear how success depends on a particular creative competence, that of blending together information from difficult sources in a novel way. Innovation is neither technology push nor demand pull; rather it is a subtle and varying blend of the two (Langrish *et al.*, 1972; Mowery and Rosenberg, 1979; Freeman, 1984; Georghiou *et al.*, 1986). It is this experimental capability of capitalism which is arguably more significant than its efficiency properties, and it is certainly this decentralised and localised creativity which marks the evolutionary nature of economic change (Antonelli, 1993). As Hayek (1948) emphasised, the process of market competition is essentially a creative process of discovery, and it is counterproductive to conceive of such a process in the context of perfect knowledge and perfect foresight. But, equally, policy makers are part of the same discovery process and are subject to the same limitations as the individuals whom they seek to influence.

A policy dichotomy

Provided one accepts the idea of technology design configurations and their embodiment in firm-specific innovation possibility frontiers, one can immediately distinguish two broad categories of technology policy. On the one hand, policy can induce firms to shift around their given innovation possibility frontiers, that is, to apply more or less innovative effort. On the other hand, policy can seek to shift the innovation possibility frontiers in a productivity enhancing fashion. However, to apply this dichotomy the policy maker must identify the relevant design configurations and judge the current possibilities for innovation within any given design configuration. The scope for technological improvement, the likely productivity of innovative effort, the significance of developments in the underpinning knowledge bases and their location in different institutions must be understood in some detail if policy is not to collapse into vague generalities. In short, a technology systems perspective is central to the effective pursuit of policy. Each technology is different in terms of the relevant institutions and dynamic processes of improvement, and it is on a comprehension of these differences that the formulation of technology policy depends. That the technology system which supports innovation in agriculture is quite different from that which supports innovation in aeronautics, for example, has long been recognised. Our conclusion is that this insight carries one to a much finer level of analysis, namely to individual design configurations which are the building blocks of technological advance. Carlsson (1992) makes this abundantly clear, as do the recent findings of Malerba and Orsenigo (1992) which emphasise the systematic differences in the innovation process across different technology classes, differences which are reasonably similar across advanced countries.

With this policy dichotomy in mind we can now propose a simple classification of technology policy issues. We present this in terms of the general choices which policy makers face:

—choices to support the development of or the application of technology;
—choices about the particular configurations on which policy will focus;
—choices between knowledge, skills and artefacts as the primary targets of policy support;
—choices about the particular firms and supporting institutions which will be the channels to improve technology;
—choices to support formal R&D programmes or less tangible learning process; and
—choices to formulate policy in isolation or in joint action with other nations.

In short, technology policy can focus on technology, on the institutions developing technology and on different stages in the innovation process. No wonder that it is so complicated an area of policy making.

3. Technology systems and national systems of innovation

At this point the question arises of how one might categorise technology policy in the light of the above observations. A useful place to begin is with Justmann and Teubal (1986) who have advocated a distinction between policies directed (strategically) at the infrastructure of elements in the economy which facilitate innovation, and those which are directed (tactically) at the development of specific technologies. More recently, the infrastructure aspects have been brought together with the concept of a national system of innovation (Freeman, 1987; Lundvall, 1988, 1993; McElvey, 1991). A national system of innovation is that set of distinct institutions which jointly and individually contribute to the development and diffusion of new technologies and which provides the framework within which governments form and implement policies to influence the innovation process. As such it is a system of interconnected institutions to create, store and transfer the knowledge, skills and artefacts which define new technologies. The element of nationality follows not only from the domain of technology policy but from elements of shared language and culture which bind the system together, and from the national focus of other policies, laws and regulations which condition the innovative environment. In the operation of national systems, governments play an important part in their support of science and technology generally and in their procurement of technologies to meet the needs of the executive. To define such a system empirically one must locate its boundaries, its component institutions and the way in which they are linked together (OECD, 1992). Many institutions are involved: private firms working individually or in collaboration; universities and other educational bodies; professional societies and government laboratories; private consultancies and industrial research associations. Each national system reflects a strong division of labour, and owing to the economic peculiarities of information, a predominance of co-ordination by non-market means. When organised appropriately, national systems can be a powerful engine of progress. Poorly organised and connected, they may seriously inhibit the process of innovation (Freeman, 1987).

Among modern industrial societies, private firms with an explicitly defined R&D function are key elements in any national system of innovation. Their motivation is to improve profitability through product and process innovation, by creating technology of an essentially proprietary nature. They are the primary institutions for designing and developing new technological artefacts and for applying them in the search for competitive advantage. In the process they also have a major impact on the skill and knowledge dimensions of technology, particularly the development of tacit knowledge. Some large firms also make considerable efforts in many applied and engineering sciences. The research budgets and facilities of some of these firms would be the envy of many a well-founded university department. By contrast, universities and other educational establishments are only minimally concerned with the development of artefacts, and make their major contributions in terms of knowledge and skills. Universities are composed of highly specialised groups of individuals, advancing knowledge and training students in the basic methods, findings and operating procedures of distant disciplines. Unlike firms, universities and the science and engineering departments they contain are essentially open institutions committed to widespread dissemination of knowledge (Nelson, 1987). Some of the research is fundamental in nature but substantial proportions of university research effort are devoted to the applied or so-called transfer sciences (OECD, 1992), which act as a bridge between fundamental science and technology. Computer science, civil engineering, pharmacology, plant breeding science and medical science are typical transfer sciences, each one tied to identifiable technological activities while drawing on insights from a range of fundamental disciplines. Universities not only create new knowledge, they also act as repositories of the stock of established knowledge which may have important generic implications for a whole range of technologies including traditional ones. Indeed, the closeness of different industries to the science base varies considerably, and within industries it can change markedly over time. Public research laboratories often play important roles either in transfer sciences or in underpinning the infratechnology of standards and metrology which is vital to the innovation system (Tassey, 1991). Private consultancies, professional societies and industrial research associations also play significant roles as bridging institutions between the worlds of industry and academic research.

That the division of labour in national systems is reflected in separate institutions for science and technology is of considerable significance for the connectivity on which their creativity depends. They reflect different cultures, responding to different research mechanisms and having different objectives. The boundary between them is almost certain to be fractured. As Dasgupta and David (1987, 1991) have emphasised, the science system is not profit-motivated and responds to a complex of motives, some arising from within disciplines and the search for priority in discovery, and others arising from the reward mechanisms for teaching and administration in universities. By contrast, the world of technology is profit-oriented, it works with relatively short-term horizons and although priority in invention is important, priority is incompatible with unrestricted public disclosure. Moreover, peer review and market selection are quite different mechanisms for distributing rewards.

While it is therefore possible and sensible for some purposes to identify differences between science policy and technology policy, there remains from the national innovation system perspective a crucial interface around which policy must be integrated. This interface is concerned with drawing scientific and engineering knowledge more effectively into the design and development activities of firms. Management of this interface creates a number of difficult problems. Since science and technology compete for many of the same skills, how should policy influence the distribution of creative talent between the two worlds? What should be the appropriate balance between research and skill formation in higher education institutions? If science is to be directed more to supporting innovation, a number of questions need to be addressed. Is there to be more emphasis on the transfer sciences, or a greater use of extrinsic non-scientific criteria in the allocation of scientific funds (Wienberg, 1967)? Would closer links with technology together with research sponsorship from industry undermine the openness of science and thus its capacity to verify results and stimulate competitive development (Gibbons, 1987)? Is it best to design a policy to foster 'exploitable areas of science' through existing university institutions or through new bridging research institutions closely linked with industry? While these questions do not at all exhaust the domain of science policy proper, they cover a highly significant proportion of the policy issues on which national innovation systems must depend.

To summarise, national innovation systems are to various degrees pluralistic in nature. Strongly based on the division of labour, their component institutions make complementary contributions to the innovation process, but they differ significantly with respect to motivation and with respect to a commitment to dissemination of the knowledge they generate. Science is not fully open, nor is technology fully closed; rather they lie towards different ends of the same spectrum. They also differ in size and in the mechanisms by which they accumulate knowledge. These differences are of considerable significance in understanding how well the various components of a national system interconnect. No institution can hope to be self-contained in its technological activities. Firms, even large firms, have to rely on knowledge from other sources and access to external knowledge can be of the first importance in raising the efficiency with which technologies are advanced (Gibbons and Johnson, 1974). This is especially so in the early stages of the development of a technology or whenever that technology has a rapidly changing knowledge base.

In practice, connectivity is achieved via a variety of mechanisms. Mobility of scientists and technologists in the labour market and collaboration agreements to develop technology are important formal mechanisms linking firms. Links between firms and universities are often instituted through grants and contracts for research, especially in the transfer sciences. In recent years increased emphasis has been devoted to the various informal networks which provide the connections within national systems. In this regard, Lundvall (1988) and Anderson (1992) have emphasised links between user firms and their suppliers, while von Hippel (1988) and Schrader (1991) have drawn attention to the significance of informal but 'balanced trading' of knowledge which takes place between engineers in different firms in the same industry. Such informal networks are important routes for technology transfer and for the transfer of more tacit knowledge. They reflect the important fact that scientists and technologists are members of common communities of practitioners with a common background in the methods of approach to problem solving: to use de Solla Price's phrase, they share common 'instrumentalities' (1984). De Bresson and Amesse (1991) have made the useful suggestion that we see networks as economic clubs acting to internalise the problems of effective knowledge transmission. To this degree, networks are a substitute both for formal markets and for organisational integration. They fall within the perimeter of non-market devices by which firms seek to co-ordinate their activities with other firms and with other knowledge-generating institutions (Richardson, 1972; Langlois, 1992). However, much remains to be discovered about the operation of different kinds of networks—scientific, technological and industrial—and in particular the ways in which different networks may interact. The costs of and time taken to establish networks are also little understood at present, as are the role of networks in limiting the decision horizons of firms, locking them into conventional technological attitudes which become self-reinforcing (Torre, 1992). Moreover, as McDonald (1992) has emphasised, formal collaboration and informal network mechanisms may be in conflict as innovative support mechanisms.

It is clear that much is yet to be learnt about the structure and development of national innovation systems (Nelson, 1992A; Lundvall, 1992). Nonetheless, some rich findings have already been obtained. In his study of the Japanese innovation system, Freeman (1987) has outlined the important role of MITI in promoting technological co-ordination between firms, and the network patterns of technology sharing within areas in the *Keiritsu* system. Malerba (1991) has identified, in the context of the Italian national system, a sharp dichotomy between two independent subsystems: one based on flexible networks of small and medium-sized firms, often co-located in distinct industrial districts; the other based on the universities, public research laboratories, and large firms performing R&D. He ventures to suggest that the former has been more effective than the latter in the post 1950 technological development of the Italian economy. Since national systems provide the context for technology policy, such a detailed understanding of these factors is clearly necessary. In particular, it is important to identify whether the appropriate boundaries are truly national (Carlsson and Stankiewitz, 1991). Science has always been international in its scope and it is increasingly the case that major R&D expenditure is undertaken by multinational firms with laboratories in several countries. In his study of the British innovation system, Walker (1991) has drawn attention to the fact that the proportion of national R&D carried out by foreign multinationals increased threefold to 13% of the total in the twenty or so years to 1988. Patent statistics also support the view of an increasing proportion of the UK's innovation activity being under the control of foreign firms (Patel and Pavitt, 1991). National firms in some industries are also observed to be developing detailed networks of international alliances to share knowledge and develop technology (Hagedorn and Shakenraad, 1990). To the extent that national systems are so interconnected, technology policies in one country will spill over to affect other countries, and one could easily foresee the emergence of a beggar-thy-neighbour effect in which policy makers in different countries compete to attract R&D-intensive companies. As Carlsson and Stankiewitz rightly point out, since science is intrinsically international in outlook, the growing 'scientification' of technology naturally opens up the nature of a technology system. Yet the national unit may also be too broad to understand the complete dynamics of technological accumulation. Instead, one may have a number of distinct technology-based systems each of which is geographically and institutionally localised within the nation but with links into the supporting national and international systems. This is indeed the conclusion of an important Swedish study (Carlsson, 1992) which finds that the institutional framework varies considerably according to the technological area in question. Links with science, interaction between competent users and suppliers, and the role of the public research institutions each varies significantly in its contribution to the innovation process. All this lends strong support to the view that integrated areas of technological activity form the natural frame for policy invention, though how these areas are to be defined and identified is not a trivial matter.

Although much remains to be clarified in this area, the concept of innovation systems is of crucial importance to the policy debate, even though they vary considerably across countries (Nelson, 1992B). They encourage policy makers to think in terms of institutions and their connectivity and thus to address the mechanisms by which policy is translated into shifts in the innovation possibility frontiers of firms. National boundaries clearly define the domain for policy making in the first instance, although increasingly policy making can be interpreted in a multi country context, as with the European Framework programme (Eilon, 1992). The issue for policy making is to be aware of how different technologies are promoted by different accumulation systems, and the extent to which these systems are connected internationally.

From the above account one conclusion is beyond contention: namely, that while firms are the primary actors in the generation of technological artefacts, their activities are supported by the accumulation of knowledge and skills in a complex milieu of other research and training institutions. Technology policy cannot be simply about the technological activities of firms; it must necessarily encompass the wider context.

Conclusion

Downie (1956) has neatly summarised the conditions for a progressive evolutionary process as follows: efficient firms must be able to grow relatively to less efficient rivals; firms must have sufficient resources to experiment with new technologies; and they must have sufficient incentives, that is, a sufficient degree of appropriability of innovation, to justify the risks of investment. From the evolutionary perspective two major policy questions follow. Is the national innovation system an adequate experimental system in that it generates an appropriate pattern of technological change consistent with policy objectives? If so, it is likely to be a pluralist system supporting many different sources of innovation with an emphasis on the diversity of micro level activity rather than a centrally driven conception of the innovation process. In such a context the coupling together of institutions in the national system is of prominent importance. Enhancing the operation of the national system is the major route to increasing the creativity of firms. The second major issue is the openness of the competitive process: that every established market position can be challenged by some other innovating firm. Barriers to innovative entry and the efficiency of market selection processes are major concerns of the policy maker here, and it is clear that they are inseparable from aspects of competitive policy more generally. In conclusion, one of the major contributions of the evolutionary school has been its insistence that the pattern of technological innovation depends on much more than the behaviour of individual firms. It is this that has lead us directly to the idea of technology systems and national systems of innovation, and it is around the operation of these systems that policy should be formed.

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