Technological paradigms and technological trajectories

A suggested interpretation of the determinants and directions of technical change

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The procedures and the nature of "technologies" are suggested to be broadly similar to those which characterize "science". In particular, there appear to be "technological paradigms" (or research programmes) performing a similar role to "scientific paradigms" (or research programmes). The model tries to account for both continuous changes and discontinuities in technological innovation. Continuous changes are often related to progress along a technological trajectory defined by a technological paradigm, while discontinuities are associated with the emergence of a new paradigm. One-directional explanations of the innovative process, and in particular those assuming "the market" as the prime mover, are inadequate to explain the emergence of new technological paradigms. The origin of the latter stems from the interplay between scientific advances, economic factors, institutional variables, and unsolved difficulties on established technological paths. The model tries to establish a sufficiently general framework which accounts for all these factors and to define the process of selection of new technological paradigms among a greater set of notionally possible ones.

The history of a technology is contextual to the history of the industrial structures associated with that technology. The emergence of a new paradigm is often related to new "schumpeterian" companies, while its establishment often shows also a process of oligopolistic stabilization.

* Previously at the Sussex European Research Centre. I am grateful to R. Nelson, W. Walker, D. Jones, M. Salvati, A. Merin, L. Bucciarelli and two anonymous referees for their comments and criticisms on previous drafts. The responsibility for this draft is obviously mine. A version of this research, more focussed on the effects of technical change upon long-run patterns of growth, is appearing in C. Freeman (ed.), *Technical Innovation and Long Waves in World Economic Development*, IPC Press, Guildford, 1982 (forthcoming).

Research Policy 11 (1982) 147–162
North-Holland Publishing Company

1. Introduction

The strict relationship between economic growth and change, on the one hand, and technical progress on the other is a rather evident and well recognized "fact" in economic thought. The nature of the relationship between the two, however, has been a much more controversial issue of economic theory. The theoretical problem concerns the direction of causal relationship, the degree of independence of technical change vis-a-vis endogenous market mechanisms – both in the short and long run, – the role played by institutional factors, the determinants of the "rate and direction" of innovative activity. Theories of technical change have generally been classified into two broad categories, namely "demand-pull" and "technology-push" theories. The distinction is self-explanatory and relates to the degree of autonomy of the innovative activity from short-run changes in the economic environment. Section 2 of this paper will attempt a brief critical review of the main difficulties of both approaches and in particular of demand-pull theories. We will try to show that these latter interpretations present a rather crude conception of technical change, as an essentially reactive mechanism, based on a "black box" of readily available technological possibilities. Moreover this conception contradicts substantial pieces of empirical evidence. On the other hand, extreme forms of technology-push approaches, allowing for a one-way causal determination (from science to technology to the economy) fail to take into account the intuitive importance of economic factors in shaping the direction of technical change.

Section 3 will attempt an interpretation of the process of innovative activity, suggesting that there are strong similarities between the nature and the procedures of "science" – as defined by modern epistemology – and those of "technology". The parallel is still rather impressionistic, but leads to the definition of technological paradigms (or technological research programmes) with many features in common with scientific paradigms (or scientific reseach programmes).

We shall define a "technological paradigm" broadly in accordance with the epistemological definition as an "outlook", a set of procedures, a definition of the "relevant" problems and of the specific knowledge related to their solution. We shall argue also that each "technological paradigm" defines its own concept of "progress" based on its specific technological and economic trade-offs. Then, we will call a "technological trajectory" the direction of advance witin a technological paradigm.

Moreover, we shall analyze the role played by economic and institutional factors in the selection and establishment of those technological paradigms and the interplay between endogenous economic mechanisms and technological innovations, once a "technological paradigm" has been established.

Section 4 will consider some implications of the model with respect to industrial structures. In particular, we shall try to translate the logical distinction between the process of search for new technological patterns and their establishment into an historical distinction, along the development of an industry, between a "schumpeterian" phase of emergence of that industry and its "maturity". We do not provide in this work any empirical backing (or very little). An application of the model to the semiconductor industry can be found in another work by the author [7]. Even that cannot be considered an adequate test of its interpretative capability which should be tried upon different technologies and longer time spans. The conclusions in section 5 suggest some of the possible directions of inquiry, together with some implications in terms of economic theory and of public policies.

This paper does not aspire to provide a "general theory" of technical change. It simply attempts to focus on questions like "why did certain technological developments emerge instead of others?" "Are there regularities in the process of generation of new technologies and in technical progress thereafter?" "Is there any regularity in the functional relationship between the vast number of economic, social, institutional, scientific factors which are likely to influence the innovative process?" Our answers to these questions are necessarily tentative. In some ways our model could be considered in itself as an "outlook", an interpretative grid, focussing on questions often neglected by orthodox economic theory which is mainly concerned with questions of instantaneous adjustments instead of problems of long-run transformation of the economic and institutional environment.

2. A critical review of the theories of technical change

Although everyone recognises, that there can be – and generally are – different and contextual origins of inventive activity, in the economic literature there has been a substantial effort to define the common elements among a wide range of inventions and/or innovations,[1] together with the search for some kind of "prime mover" of inventive activity. In the literature on the subject, one used to define two different basic approaches, the first pointing to market forces as the main determinants of technical change ("demand-pull" theories) and the second defining technology as an autonomous or quasi-autonomous factor, at least in the short run ("technology-push" theories). Such a clear-cut distinction is of course hard to make in practise but remains useful for the sake of exposition: there is indeed a fundamental distinction between the two approaches and that is the role attributed to market signals in directing innovative activity and technical changes. It seems to us that this distinction (the role attributed to market signals), although overlapping a great deal with the distinction "demand-pull" versus "technology-push" theories, is indeed the main core of the discussion.

[1] "In this schumpeterian distinction an '*invention*' is an idea, a sketch or a model for a new or improved device, product, process of system. Such inventions ... do not necessarily lead to technical *innovations*... . An innovation in the economic sense is accomplished only with the first *commercial* transaction involving the new product, process ...", Freeman [12], p. 22. Accepting this distinction, the borderline is in that the new device or process is not only potentially *marketable* but actually *marketed*. I will recall the distinction when discussing the role of the market.

Let us consider first a "pure" demand-pull theory. As discussed exhaustively in a comprehensive critical paper by Rosenberg and Mowery [31], the causal prime mover in those theories is some supposed "recognition of needs" by the productive units in the market, to which follows their attempts to fulfill those needs through their technological efforts. This "pure" market-pull theory would run more or less as follows (both causally and chronologically). (1) There exists a set of consumption and intermediate goods, at a given time, on the market, satisfying different "needs" by the purchasers. In passing, one must notice – as we shall recall below – that the same definition of "needs" is quite ambiguous: at the one extreme one may define them in very general "anthropological" terms (the needs to eat, have shelter, communicate, etc.) but then they express a total indifference to the way they are satisfied and do not have any economic relevance; or, at the other extreme, "needs" are expressed in relation to the specific means of their satisfaction, but then each "need" cannot emerge before the basic invention to which it is related.[2] (2) Consumers (or users) express their preferences about the features of the goods they desire (i.e. the features that fulfill their *needs* the most) through their patterns of demand. This is another way of saying that demand functions are determined by the existence and the forms of utility functions. We may assume now that pattern of demand change (i.e. that the demand function shifts upward or downward) or just that – which is basically the same – in a growing economy, given the relative prices of the considered commodities, the income elasticities of demand of the latter are different. (3) The theory would argue that, with a growing income relaxing the budget constraint of the consumers/users, the latter demand proportionally more of the goods which embodied some relatively preferred characteristics (i.e. those which more adequately satisfy their needs). (4) At this point the producers enter into the picture, realising – through the movements in demand and prices – the revealed needs of the consumers/users: some "utility dimensions" have a higher weight (there is more *need* for them). (5) Here the proper innovative process begins, and the successful firms will at the end bring to the market their new/improved goods, letting again the "market" (as above defined) monitor their increased capability to fulfill consumers' needs.

Of course not even the most extremist "demand-pull" theorist would support entirely this crude view.[3] The basic argument however maintains that there *generally exist* a *possibility* of *knowing a priori* (before the invention process takes place) the *direction* in which the market is "pulling" the inventive activity of producers and furthermore that an important part of the "signalling process" operates through movements in relative prices and quantities. Thus, in this perspective, the innovative process can be placed – although with consistent difficulties – inside the neo-classical framework.[4] With respect to producers, this viewpoint implies that the "choice sets are given and the outcomes of any choice known".[5] The assumption of "known outcomes" could perhaps be relaxed to introduce risk and stochastic variables, but the first assumption has to be maintained (given and finite sets of choices).

The viewpoints outlines above might be criticised on different levels, namely: (1) the general theory of prices as determined by supply and demand functions; (2) the difficulties of defining demand functions as determined by utility functions and the same feasibility of a "utility" concept; and (3) the logical and practical difficulties in interpreting the innovative process through this approach.

The first question is undoubtedly the biggest one because it could undermine the entire theory

[2] In other words, in the first definition, the "need" to move around can be satisfied either through a horse or a space-shuttle. In the second definition, obviously the "need" for a space-shuttle cannot emerge before the space-shuttle itself is conceived.

[3] But this "one-directional" determination of the innovative activity from consumers/users needs to producers' innovative output appears clearly in studies like that of Myers and Marquis [21].

[4] In a "weaker sense", it is apparent that within this approach the innovative mechanism operates in the same way as the usual mechanism of determination of prices and quantities in a general equilibrium analysis. In a "stronger sense", it does not appear impossible – given restrictive assumptions – to construct a neoclassical general equilibrium analysis which takes account of this kind of innovative activity. For the difficulties of this approach, see below.

[5] Nelson and Winter [24] in Belassa and Nelson [4]. This work, to which I will refer again later, is, as far as I know, one of the first attempts to formalise a non-neoclassical model of technical progress, embodying rather complex assumptions about firms' attitudes toward, and responses to the innovative activity.

on which this approach is based upon. This is not the place though to deal with that issue [6] and the discussion will be restricted to the third point.

With respect to this more circumscribed question, some significant problems throw doubts on the entire adequacy of demand-based theories of innovations. (1) A theory of innovation is supposed to explain not only (and not even primarily) "incremental" technical progress on the existing products/processes, but first of all it is meant to interpret major and minor technological breakthroughs. As far as the latter are concerned the range of "potential needs" is nearly infinite and it is difficult to argue that these would-be demands can explain why, in a definite point in time, an invention/innovation occurs (see Rosenberg [30] and Rosenberg and Mowery [31]).

(2) Even after allowing *a priori* recognition of a "need", it is difficult to explain with this approach what happens between that recognition by producers and the final outcome of a new product. Either we have to assume a set of technological possibilities already in existence (but then we must wonder why those possibilities have not been exploited before [7]) or we must assume a limited time lag between research and the outcomes of that research. The concept of technology (and, at least indirectly, of science) underlying this appraoch is of a very versatile and "responsive" mechanism which can be directed with limited effort and cost in one direction or another. To avoid a crude conception of technology as a "freely available blackbox", there have been some efforts in the theory to consider information as an expensive commodity. [8] Those attempts, while representing a big advance in that they account for the microeconomic aspects of technological efforts (which have a cost and an expected return for each single firm) and also in that they somehow account for the interrelation science-technology-production, do not seem to be able to consider the entire complexity of scientific and technological procedures. [9]

To summarize, there appear to be three basic weaknesses in "strong" versions of demand-pull approaches: first, a concept of passive and mechanical "reactiveness" of technological changes vis-a-vis market conditions; second, the incapability of defining the *why* and *when* of certain technological developments instead of others and of a certain timing instead of others; third, the neglect of changes over time in the inventive capability which do not bear any *direct* relationship with changing market conditions.

The theoretical ambiguities of demand-pull theories seem inevitably reflected in the empirical studies on the determinants of innovation (critically reviewed in Rosenberg and Mowery [31]). Not surprisingly, most of the studies find that "market is important in determining successful innovations". I find myself in agreement with Rosenberg and Mowery though, in that most of the studies with a demand-pull approach fail to produce sufficient evidence that "needs expressed through market signalling" are the prime movers of innovative activity (see [31]). And this is precisely the question at stake. Other important empirical works on the contrary point to multivariables explanations of innovative activity [10] and

[6] For our purposes it is enough to mention that if we assume, at any point in time, fixed coefficient of production and constant return to scale, variations in the quantities do not affect relative prices. Therefore we are bound to loose an important part of the "signalling" mechanism. On the other hand a demand/supply theory of prices might be abandoned for the unavoidable difficulties of its theory of factor prices and distribution.

[7] Except in the cases in which an already existing *invention* can become a marketable *innovation*, at a certain point in time, due to changes in income distribution, or in relative prices.

[8] Generally with particular features such as limited appropriability, indivisibility, etc. See Arrow [2 and 3].

[9] The effort of "endogenising" the production of knowledge, equated to the production of a commodity, accounts for the evident trend, at least in this century, toward a greater contribution to the innovative activity by institutional centres directly related to production of scientific and technological advances (and first of all by R&D facilities of big corporations). This schumpeterian view (Schumpeter [39]) is challenged by some scholars, for example Jewkes et al. [16] who maintain that a great percentage of innovation is still attributable to private inventors. For an exhaustive discussion of this issue, see Freemen [12]. The problem crucial to our discussion, however, still remains: how do technological efforts operate? Can the direction of technological advances be pushed almost frictionless in any direction? Can the lags between an assumed "market demand" and the technological response be considered fairly limited in time' etc. For a critical discussion of the "black-box approach" to technology, see again Rosenbreg [30 and 31].

[10] See project SAPPHO [36] Teubal, Arnon, Trachtenberg [44] and Teubal [45]. Those studies, and especially the first are primarily concerned with determinants of success and failures in industrial innovations and not so much with the determinants of the direction of the innovative activity as such.

to the role of science and technology in fostering innovation along a path leading from initial scientific advances to the final innovative product/process. [11]

On a more general level, an analysis of the technology and generally "supply-side" factors of innovative process can be found in Freeman [12], Pavitt and Wald [28] and Pavitt and Soete [29]. [12] Some aspects of the innovative process can, in our view, be considered rather established. Among them:

(1) The increasing role (at least in this century) of scientific inputs in the innovative process.

(2) The increased complexity of R&D activities which makes the innovative process a matter of long-run planning for the firms (and not only for them) and witnesses against an hypothesis of prompt innovative answer by producers vis-a-vis changes in market conditions.

(3) A significant correlation between R&D efforts (as proxy of the inputs in the innovative process) and innovative output (as measured by patent activity) in several industrial sectors [13] and the absence, in *cross-country* comparisons, of evident correlations between market and demand patterns on the one hand, and innovative output, on the other.

(4) The intrinsically *uncertain* nature of the inventive activity which plays against an hypothesis of limited and known sets of choices and outcomes.

The difficulties incurred by strong versions of "technology-push" theories are in some respects opposite to those discussed above: there, it was the difficulty to take into account the complexity, the relative autonomy and the uncertainty associated with technological change and innovation. Here, the problem arises in relation to the obvious fact that "economic factors are important indeed" in shaping the direction of the innovative process. The process of growth and economic change, variations in distributive shares and in relative prices are all affecting the direction of the innovative activity and one feels quite uneasy in accepting a view of technical progress – paraphrasing Joan Robinson – as "given by God, scientists and engineers". The main theoretical task with respect to supply-side approaches is the avoidance of a one-directional conception "science – technology - production" in which the first would represent a sort of exogenous and neutral *deus-ex-machina*. One realises that, in actual fact, there is a complex structure of feed-backs between the economic environment and the directions of technological changes. A tentative theory of technical change should define – in a form as general as possible – the nature of these inter-active mechanisms. In different ways demand-pull and technology-push theories appear to fail to do so. In the former, technical change and innovation are a basically *reactive* mechanism which certainly shows some consistency with the traditional assumptions of neo-classical economics (consumer sovereignty, optimising behaviours, general equilibrium, etc.) but presents also unavoidable logical and empirical difficulties. On the other hand, if supply-side factors manifest some independence – at least in the short-run – from market changes, it must be possible to show how they are affected in the long run by the economic transformation.

3. A proposed interpretation: Technological paradigms and technological trajectories

Economic theory usually represents *technology* as a given set of factors' combination, defined (qualitatively and quantitatively) in relation to certain outputs. Technical progress is generally defined in terms of a moving production possibilities curve, and/or in terms of the increasing number of producable goods. The definition we suggest here is, on the contrary, much broader. Let us define technology as a set of pieces of knowledge, both directly "practical" (related to concrete problems and devices) and "theoretical" (but practi-

[11] See the TRACES Project [15].

[12] In the first study, an analytical examination of various innovations in the fields of process plant, synthetic materials and electronics considers the role of scientific and organised technological efforts in determining innovation, while the second, in a cross-country analysis, compares demand and market-related factors with technological organisational and supply-related factors. Finally, the third relates indicators of economic performance to indicators of technical efforts and innovativeness (in a causal relationship which goes from the latter to the former).

[13] See also the important findings by Pavitt and Soete [29] and Soete [42]. Moreover, if we measure innovative output in terms on increase in productivity (as a proxy of technical progress) the impact of research efforts is significant (see for example Mansfield [19] and Terleckyi [43]).

cally applicable although not necessarily already applied), know-how, methods, procedures, experience of successes and failures and also, of course, physical devices and equipment. Existing physical devices embody – so to speak – the achievements in the development of a technology in a defined problem-solving activity. At the same time, a "disembodied" part of the technology consists of particular expertise, experience of past attempts and past technological solutions, together with the knowledge and the achievements of the "state of the art". Technology, in this view, includes the "perception" of a limited set of possible technological alternatives and of notional future developments. This definition of technology is very impressionistic, but it seems useful to explore the patterns of technical change. One can see that the conceptual distance between this definition and the attributes of "science" – as suggested by modern epistemology – is not so great.

We shall push the parallel further and suggest that, in analogy with scientific paradigms (or scientific research programmes), there are "technological paradigms" (or technological research programmes). [14]

A "scientific paradigm" could be approximately defined as an "outlook" which defines the relevant problems, a "model" and a "pattern" of inquiry.

"The success of a paradigm ... is at the start largely a promise of success discoverable in selected and still incomplete examples. Normal science consists in the actualization of that promise, an actualization achieved by extending the knowledge of those facts that the paradigm displays as particularly revealing, by increasing the extent of match between those facts and the paradigm's predictions, and by further articulation of the paradigm itself" (Kuhn [14], pp. 23–41).

In broad analogy with the Kuhnian definition of a "scientific paradigm", we shall define a "technological paradigm" as "model" and a "pattern" of solution of *selected* technological problems, based on *selected* principles derived from natural sciences and on *selected* material technologies.

First of all, the similarities relate to the mechanism and procedures of "science", on the one hand, and those of technology, on the other. [15] As a scientific paradigm determines the field of enquiry, the problems, the procedures and the tasks (the "puzzles", in Kuhn's words), so does "technology" in the sense defined above (it would perhaps be better to talk of "cluster of technologies", e.g. nuclear technologies, semiconductor technologies, organic chemistry technologies, etc.).

As "normal science" is the "actualization of a promise" contained in a scientific paradigm, so is "technical progress" defined by a certian "technological paradigm". We will define a *technological trajectory* as the pattern of "normal" problem solving activity (i.e. of "progress") on the ground of a technological paradigm.

More precisely, if the hypothesis of technological paradigm is to be of some use, one must be able to assess also in the field of technology the existence of something similar to a "positive heuristic" and a "negative heuristic". [16] In other words a technological paradigm (or research programme)[17] embodies strong prescriptions on the *directions* of technical change to pursue and those to neglect. Given some generic technological tasks (one could call them generic "needs") such as, for example, those of transporting commodities and passengers, producing chemical compounds with certain properties or switching and amplifying electrical signals, certain specific technologies emerged, with their own "solutions" to those problems and the exclusion of other notionally possible ones: in our three examples, historically these

[14] On scientific paradigms, see Kuhn [14] and on scientific research programmes, Lakatos [17]; for a thorough discussion Musgrave and Lakatos [22]. One does not have any ambition here to argue "what science is" or tackle the epistemological disputes on the differences between the Kuhnian approach and Lakatos' one. For our purposes the degreee of overlap between the two approaches is great enough to borrow from them a few basic definitions of science which they have in common.

[15] A very stimulating paper by Bonfiglioli [5] defines "science" as a "particular technology". Although the aims of that paper are different from ours here, there is in common the strict similarity and overlapping between "science" and "technology" and the role of institutional factors in determining the direction of both (see below).

[16] "... The continuity evolves from a genuine research programme adumbrated at start. The programme consists of methodological rules: some tell us what paths of research to avoid (*negative heuristic*) and others what paths to pursue (*positive heuristic*)". Lakatos [17], p. 47.

[17] Note that here one is impressionistically using the two concepts as equivalent.

technologies were the internal combustion engine, petrochemical processes and semiconductors, respectively. Technological paradigms have a powerful *exclusion effect*: the efforts and the technological imagination of engineers and of the organizations they are in are focussed in rather precise directions while they are, so to speak, "blind" with respect to other technological possibilities. At the same time, technological paradigms define also some idea of "progress". Again in analogy with science, this can hardly be an absolute measure but has some precise meaning within a certain technology. The identification of a technological paradigm relates to generic tasks to which it is applied (e.g. amplifying and switching electrical signals), to the material technology it selects (e.g. semiconductors and more specifically silicon), to the physical/chemical properties it exploits (e.g. the "transistor effect" and "field effect" of semiconductor materials), to the technological and economic dimensions and trade-offs it focusses upon (e.g. density of the circuits, speed, noise-immunity, dispersion, frequency range, unit costs, etc.). Once given these technological and economic dimensions, it is also possible to obtain, broadly speaking, an idea of "progress" as the improvement of the trade-offs related to those dimensions.

The broad analogy between "science" and "technology" we have been drawing should clearly not be taken as an identity. In addition to the obvious difference related to the different nature of the "problem solving" activity, technological "knowledge" is much less well articulated than is scientific knowledge; much of it is not written down and is implicit in "experience", skills, etc. This implies also that the definition of a "technological paradigm" is bound to be much looser while the distinction between "normal activity" and "problem-shifts" is likely to be hard to make in practice. The same idea of a "technological paradigm" should be taken as an approximation, adequate in some cases but less so in others. In our view, however, the analogy keeps its validity in that both ("scientific" and "technological") activities represent strongly selective *gestalten* embodying powerful heuristics.

A crucial question relates to how an established technological paradigm emerged in the first place and how it was "preferred" to other possible ones. Let us consider "downward" the sequence science–technology–production, remembering that it is meant to be just a *logical* simplification which neglects the crucial long-run influence of the economic and technological environments upon science itself.

Even within "science", the problems and the "puzzles" *actually* tackled (and those solved) are of course much more limited in number than the total number of problems and puzzles that the scientific theories potentially allow, and even more so the pieces of theory, puzzles, possibilities of development, "passed-on" from scientific theory to "applied science" and to technology (the last two, at least, being significantly overlapping). Leaving aside temporarily the problems of feedbacks, the hypothesis is that along the stream science–technology–production, the "economic forces" (that I will define below) together with institutional and social factors, operate as a *selective device* (the "focussing device" of Rosenberg [30]). Within a large set of *possibilities* of directions of development, notionally allowed by "science", a first level of selection (at least in the overwhelming majority of research activity in the enterprise sector) operates on the basis of rather general questions like: "Is any practical application conceivable?"; "Is there some possibility of the hypothesised application being marketable?", etc. Along the down-stream from "Big Science" to production (on a path which is much easier to conceive as a continuum instead of a strictly defined discrete set of steps), the *determinateness* of the selection increases: at one end we have the "puzzle-solving activity" (Kuhn [14]) defined by scientific paradigms *stricto sensu*; at the other end we have a technology totally embodied in devices and equipment. In between, in a field that we must already call technology because it is specifically ("economically") finalised, the activities aimed at "technical progress" have still many procedures and features similar to "science", namely the problem solving activity along lines defined by the nature of the paradigm. The economic criteria acting as selectors define more and more precisely the *actual* paths followed inside a much bigger set of possible ones.

On the other hand, once a path has been selected and established, it shows a momentum of its own (Nelson and Winter [24], Rosenberg [30]), which contributes to define the directions toward which the "problem solving activity" moves: those are what Nelson and Winter [25] define as *natural* *trajectories* of technical progress [18]. A technological trajectory, i.e. to repeat, the "normal" problem solving activity determined by a paradigm, can be represented by the movement of multi-dimensional trade-offs among the technological variables which the paradigm defines as relevant. Progress can be defined as the improvement of these trade-offs. [19] One could thus imagine the trajectory as a "cylinder" in the multidimensional space defined by these technological and economic variables. (Thus, a technological trajectory is a cluster of possible technological directions whose outer boundaries are defined by the nature of the paradigm itself). Some features of these technological trajectories, defined on the basis of technological paradigms are worth considering:

1. There might be more general or more circumscribed as well as more powerful or less powerful [20] "trajectories".

2. There generally are *complementarities* among trajectories (i.e., out of the metaphor, there are strong complementarities between different forms of knowledge, experience, skills, etc.) (see Rosenberg [30 and 48]). Furthermore developments or lack of development in one technology might foster or prevent developments in other technologies.

3. In terms of our model one can define as the "technological frontier" the highest level reached upon a technological path with respect to the relevant technological and economic dimensions. [21]

4. "Progress" upon a technological trajectory is likely to retain some cumulative features: the probability of future advances is in this case related also to the position that one (a firm or a country) already occupies vis-a-vis the existing technological frontier. This is strictly consistent with Nelson and Winter's representation of technical progress at firm and industry levels, with Markovian chains. (Nelson and Winter [24]).

5. Especially when a trajectory is very "powerful", it might be difficult to switch from one trajectory to an alternative one. Moreover, when some comparability is possible between the two (i.e. when they have some "dimensions" in common), the frontier on the alternative ("new") trajectory might be far behind that on the old one with respect to some or all the common dimensions. In other words, whenever the technological paradigm changes, one has got to start (almost) from the beginning in the problem-solving activity.

6. It is doubtful whether it is possible *a priori* to compare and assess the superiority of one technological path over another. There might indeed be some objective criteria, once chosen some indicators, but only *ex post*. [22] This is one of the reasons behind the intimate uncertain nature of

[18] They suggest two general dimensions of these "natural trajectories", toward progressive exploitation of latent economies of scale and toward increasing mechanisation of operations, quoting as supporting evidence – among others – the studies by Hughes on electric power equipment, Levin on various petrochemical processes and Rosenberg [30].

[19] To take obvious examples, the trade-offs between energy consumption and horsepower in internal combustion engines or that between speed and density of the circuits in semiconductors (this refers to the comparison between bipolar and MOS technologies). A definition of technical progress in terms of multi-dimentional trade-offs is sometimes used in technological forecasting models. For a short overview, see Martino [20]. Sahal [33 and 34] utilize a similar definition of technology and technical progress, applied to individual industries and products.
After the first draft of this paper was completed, an important article by Sahal [47] was published. He suggests a "system approach" to technology and technical change, seeing it as an evolutionary and continuum process. Moreover he suggests the existence of "technological guide-posts". One can easily see the consistence of his thesis with what is argued here. We hope, in this paper, to throw some light also on the definition, emergence and selection of his "technological guide-posts" and on the implications in terms of evolution of industrial structures.

[20] Again one uses the term in analogy with epistemology: in our case a trajectory is more powerful the bigger the set of technologies which it excludes. For instance it seems that the technological paths defined by nuclear or oil power-generation equipment is very powerful, meaning that many other sources of energy (many other technologies) are excluded.

[21] One may figure that "frontier" as a set of points in a multidimensional space.

[22] For some examples on semiconductors, Dosi [7]. An important attempt to define some precise criteria of "progress" is in Sahal [34]. As should be clear from the discussion above, an unequivocal criterion can be easily identified only *within* a technological paradigm (i.e. *along* a technological trajectory). Comparisons (even *ex post*) between different trajectories might yield sometimes, although not always, to ambiguous results. In other words, it might occur that the "new" technology is "better" than the "old" one in several chosen dimensions, but it might still be "worse" in some others. One can see here a loose analogy with the epistemological discussion (whereby an "extreme" Kuhnian approach claims strict incomparability and a Popper-like approach suggests some progressive continuity).

research activity (even leaving aside the market evaluations of the results, but just considering purely technological indicators).

The role of economic, institutional and social factors must be considered in greater detail. A first crucial role – as already mentioned – is the *selection* operated at each level, from research to production-related technological efforts, among the possible "paths", on the ground of some rather obvious and broad criteria such as feasibility, marketability and profitability.

On these very general grounds, there might still be many possible technological paradigms that could be chosen. Given the intrinsic uncertainty associated with their outcomes, in terms of both technological and economic success, it is hardly possible to compare and rank them *ex ante*.[23] Other more specific variables are likely to come into play such as (1) the economic interests of the organizations involved in R&D in these new technological areas, (2) their technological history, the fields of their expertise, etc; (3) institutional variables *stricto sensu* such as public agencies, the military, etc. All these factors are likely to operate as focussing forces upon defined directions of technological development. In particular one must stress the role often played in the establishment of a particular technological trajectory by public ("political") forces. An obvious example is electronics, especially in the fields of semiconductors and computers during the first two decades of the post-war period. Military and space programmes operated then as a powerful focussing mechanism toward defined technological targets, while at the same time providing financial support to R&D and guaranteeing public procurement.[24] Other similar cases can be found throughout the modern history of technology: for example, the emergence of synthetic chemistry in Germany bears a close relationship with the "political" drive of that country towards self-sufficiency in the post-Bismarck period (see Freeman [12] and Walsh et al. [46]).

These kinds of institutional effects upon the emergence of new technologies are not a general rule: the point we want to stress, however, is the general weakness of market mechanisms in the *ex ante* selection of technological directions especially at the initial stage of the history of an industry. This is, incidentally, one of the reasons that militates for the existence of "bridging institutions" between "pure" science and applied R&D.[25]. Even when a significant "institutional focussing" occurs, there are likely to be different technological possibilities, an uncertain process of search, with different organizations, firms and individuals "betting" on different technological solutions. Proceeding in our parallel with epistemology, this resembles a world *à la* Feyerabend [11] with different competing technological paradigms: competition does not only occur between the "new" technology and the "old" one which it tends to substitute but also among alternative "new" technological approaches.

We did not say very much about *positive ex ante* criteria of selection among potential technological paradigms apart from rather general ones such as marketability or potential profitability. Another powerful selecting criterion in capitalist economies is likely to be the cost saving capability of the new technology and in particular its labour saving potential: this is obviously consistent with Nelson and Winter's suggestion of "natural trajectories" toward mechanisation and exploitation of economies of scale. Certainly in societies where industrial conflict and conflict over income distribution are structural features, substitution of machines for labour must be a powerful determinant in the search process for new technologies.[26]

More generally, the patterns of industrial and social conflict are likely to operate, within the process of selection of new technological paradigms, both as negative criteria (which possible developments to exclude) and as positive criteria (which technologies to select). In this respect, one might be able to define some long-run relationship between patterns of social development and actually chosen technological paradigms (one quite clear example could be the relationship between industrial relations at the turn of the last century and the selection and development of "tayloristic"

[23] For a discussion of uncertainty in R&D projects' evaluation, see Freeman [12].

[24] A more detailed discussion is in [7].

[25] A convincing and thorough discussion is in Freeman [12].

[26] The discussion of possible biases in cost-saving technical change, long-run cycles, etc. is clearly beyond the scope of this work. Our hypotheses on the procedures of technical change and innovation might, however, provide a possible framework for the analysis of these questions.

patterns of technical change in mechanical engineering).

Let us consider the final stage of this logical sequence from science to production, when – in cases of product innovations – a commodity is produced and sold: at this final stage markets operate again as the selective environment.[27] It must be noted that this "final selection" has a different nature from the previous stages. In the choices of the technological paths some kinds of economic indicators were operating as *a priori* directing devices among a big number of possible and wide technological choices. Here the market operates *ex post* as a selecting device, generally among a range of products already determined by the broad technology patterns chosen *on the supply side*. To further clarify the distinction, R. Nelson suggested in his comments on a previous draft of this paper, a biological analogy. The final market selection may be equated to the environmental selection on mutations (Nelson and Winter models describe mainly this "evolutionary" mechanism within the economic environment). The discussion above relates, on the contrary, to the selection of the "mutation generating" mechanisms. Thus economic and social environment affects technological development in two ways, first selecting the "direction of mutation" (i.e. selecting the technological paradigm) and then selecting among mutations, in a more darwinian manner (i.e. the *ex post* selection among "schumpeterian" trials and errors). At times when new technologies are emerging, one can often observe new ("schumpeterian") companies trying to exploit different technological innovations. Markets perform as a system of rewards and penalizations, thus checking and selecting amongst different alternatives. In this respect, the existence of a multiplicity of risk-taking actors, in non-planned economies, is crucial to the trial-and-error procedures associated with the search for new technological paths. These "actors" take risks, of course, because there are markets which allow high rewards (i.e. profits) in case of commercial success.

Incidentally, one should note that if our interpretation of the process of technical change is correct, the emergence of new technological paradigms is *contextual* to the explicit emergence of economically defined "needs". In other words, the supply-side determines, so to speak, the "universe" of possible modalities through which generic "needs" or productive requirements (which as such do not have any direct economic significance) are satisfied. (In this, one can see the element of truth contained in those sociologically-based theories suggesting needs "induced" by corporate strategies).

Changing economic conditions clearly interact with the process of selection of new technologies, with their development and finally with their obsolescence and substitution. One has therefore to analyze the feed-back mechanisms, "upward", from the economic environment to the technology (one should also consider the long-run influence of economic and technological factors upon scientific change: this is however well beyond the scope of this article). Changing relative prices and distributive share are bound to affect demand for the various commodities and the relative profitabilities in manufacturing them. Producers certainly react to these signals from the economic environment, trying to respond through technical advances. However, this often occurs within the boundaries of a given technological trajectory, which might either be conducive or place increasing constraints to any development consistent with the "signals" the economic environment is delivering.[28] Difficulties and unsolved technological puzzles and problems, to use again the Kuhnian language, operate upward as focussing devices, sometimes put pressure on other technological fields to go further in their problem solving, and finally facilitate or hinder the switch to other technological trajectories. It must be stressed, however, that unsolved technological difficulties do not automatically imply a change to another "path".[29] Of course, changes in market conditions and opportunities (among which changes in demand patterns, in relative distributive shares, in costs of production, etc. are very important) continuously bring pressures "upward", at various levels, upon technological trajectories, and upon the same selection criteria on the basis of which those trajectories are chosen. But this fact does not imply by

[27] See Nelson and Winter [24].

[28] Take the example of the oil-powered internal combustion engine. Changing oil prices put an increasing pressure on oil substitution and energy saving. The scope for substitution however is limited by the technology which itself defines the range of possible technological advances.

[29] Precisely as unsolved puzzles or ("falsifications") in a scientific paradigm do not imply an alternative paradigm.

any means an assumption of malleable "ready-to-use" alternative technological paths, or, even more so, instantaneous technological responses to changes in market conditions. Furthermore an implicit consequence of what was just said is that the "upward" impact of changing economic conditions on technological research patterns seems directly proportional to the *technological determinateness* of the economic stimuli themselves.[30] So one would generally expect this determinateness to increase as one moves from consumers' goods to investment goods and to other kinds of non-properly-marke goods (such as military equip- t).

lote that changes in the economic environment a permanent feature of the system: those ianges often simply stimulate technical progress (as defined above) *along* one technological trajectory. Again in parallel with epistemology we can call it the "normal" technological activity. "Extraordinary" technological attempts (related to the search for new technological directions) emerge either in relation to new opportunities opened-up by scientific developments or to the increasing difficulty in going forward on a given technological direction (for technological or economic reasons or both).[31]

4. Technical change and industrial structures: From a schumpeterian phase to industrial maturity

We tried above to make a logical distinction between the process of search and selection on new technological paradigms and technical progress along a defined path. New technologies are selected through a complex interaction between some fundamental economic factors (search for new profit opportunities and for new markets, tendency toward cost saving and automation, etc.), together with powerful institutional factors (the interests and the structure of the existing firms, the effects of government agencies, etc.). Technical change along established technological paths, on the contrary, becomes more endogenous to the "normal" economic mechanism. This distinction between two technological phases is likely to correspond historically to two different sets of features of an industry, related to its emergence and its maturity. In the phase of economic *trial and error*, primary importance must be attributed to (1) the *institutions* which produce and direct the accumulation of knowledge, experience, etc., and (2) the existence of a multiplicity of risk-taking actors, ready to try different technical and commercial solutions. The "schumpeterian" features properly refer to this second aspect.[32]. Note that breakthroughs and innovations, in this phase, need not be developed by those schumpeterian companies themselves. There is evidence, on the contrary, that often in this century the production of major technological advances has been the result of organized R&D efforts as opposed to the "inventiveness" of individuals.[33] What matters are the attempts (either by new companies or old ones), in the first phase, to implement and commercially exploit "extraordinary technology", driven by the search for new profit and market opportunities. Often this period of emergence of new technologies is actually characterized by newly emerging firms, even in cases when the major technological advances were originally produced in established firms and institutions (semiconductors for example).[34]

In the second phase, which may often correspond to an *oligopolistic maturity*, the production, exploitation and commercial diffusion of innovations are much less divorced and technical change often becomes itself part of the pattern of "oligopolistic competition". The more a fundamental technological pattern becomes established, the more the mechanism of generation of innovations

[30] This broadly corresponds to Teubal's concept of *market determinateness* [45].

[31] It can be (and has been) reasonably argued that scientific developments themselves are fostered in the long-run by technological and economic "foci" of attention and that they are somewhat directed by the *weltanschauungen* that economic systems provide. This very wide issue concerns fields like epistemology, sociology of knowledge, etc., and it is not possible to discuss it here.

[32] Here one refers to the "first" Schumpeter of the *Theory of Economic Development* [38].

[33] A review of the discussion on the subject is in Freeman [12]. Some, however, still hold the opposite view (Jewkes et al. [16]). The history of chemical innovations is analyzed by Walsh et al. [46]. On the role of established firms in semiconductors, see [7].

[34] We try to analyze the factors which allow it, related to different attitudes toward risk, constraints facing a quick diffusion of innovations by existing firms, taxation regimes, in [9].

and of technological advances appears to become endogenous to the "normal" economic mechanism. In this respect, the possibility of enjoying temporary monopolistic (and long-run oligopolistic) positions on new products and processes appears to act as a powerful incentive to the innovative activity, improvement of existing products, etc. The perspective differential advantages accruing to successful technological and market leaders, in my view, are likely to influence and stimulate the process of innovation much more than the *ex ante* market structure as such.[35] The process of innovation itself is, of course, bound to affect the industrial structure and shape its transformation.

The establishment of a defined technological paradigm is likely to be parallelled by a process of "internalization" within companies of the so-called "externalities" related to the innovative activity, capitalizing on the previous experience of attempts, successes and failures, etc.: within an established technological paradigm the fluid market structure characterized by the "heroic entrepreneurship" often described in the literature on new industries is likely to disappear.

Both phases are likely to show some "oligopolistic power",[36] although the sources of it differ significantly: whereas in the first one, oligopolistic positions mainly relate to *dynamic* economies ("learning curve", etc.) and temporary asymmetries in relation to the capability of successfully innovating, in the second stage the origins of oligopolistic structures would relate not only to the technological progressiveness of firms but also to some *static* entry barriers (economies of scale, etc.).

5. Conclusions: Some theoretical and policy implications

We should stress, first of all, the limitations of the suggested model: the analogy between science and technology is, in some respects, "impressionistic" and the parallel should not be pushed too far without reaching decreasing returns. This notwithstanding, the model might prove useful in interpreting some important questions related to the process of technical change. First, it can explain – in rather general terms – the role of *continuity* versus *discontinuity* in technical change. "Incremental" innovation versus "radical" innovations can be reinterpreted in terms of "normal" technical progress as opposed to new emerging technological paradigms. The distinction might still be in practice difficult to draw, but nonetheless can account for the conditions which allow either "normal" progress or "extraordinary" innovative effort to take place. Second, it can throw some light on the *procedures* through which technical change occurs. The search for new products or processes is never a random process on the entire set of notional technological opportunities. Paradigms are also an "outlook" which focusses the eye and the efforts of technologists and engineers in defined directions. (This, incidentally, might have interesting implications in terms of the sociology of the firms and it would be worth studying the origins and the backgrounds of "revolutionary" engineers as compared with "normal" ones).

[35] The relationship between market structure and incentives to innovate has produced significant discussion in the literature. See among other, Arrow [2], Needham [49], Shrieves [40], Scherer [50] and Salvati [35]. Salvati shows, under rather general assumptions that the incentive to *introduce innovations* is not generally lower under oligopolistic conditions than in competitive ones. Arrow, in his seminal article, states the opposite view (at least as far as process innovations are concerned), with respect to the incentive to *produce* innovations. Two implicit and rather questionable assumptions are, however, crucial to his argument. First, one must assume that there are no economies of scale and no minimum threshold in R&D activities, no cumulativeness of technical progress, or, alternatively, that market mechanisms induce an allocation of innovative activities amongst competitive actors, *as if* they were a simple monopolist. Second, one must assume that the "degree of private appropriability" of the innovations is the same under competitive and oligopolistic conditions. Needham offers a thorough and rigorous treatment of R&D and innovation decisions under neo-classical behavioural assumptions on firms' conduct. He shows that, depending on elasticities and expected rivals' reactions, more or less everything may be expected to happen (i.e. that structural variables like concentration, demand elasticities, etc. may have effects of opposite signs upon firms' propensity to innovate).

One can find in Soete [41] a critical analysis of the available evidence on the subject and a strong support for a "Schumpeterian view". Nelson and Winter [24] interpret, in a genuinely dynamic framework, the process of innovation under oligopolistic conditions and market structure itself, in their models, as an endogenous variable.

[36] I try to assess the existence of the determinants of oligopolistic margins in the semiconductor industry in [9].

Third, the idea of paradigms and trajectories can account for the often observable phenomenon of *cumulativeness* of technical advances (within an established trajectory). At the same time the intrinsic *uncertainty* associated with technological shifts can be clearly appreciated. The same idea of "technical progress' might be rigorously defined within one technological path (as the improvements of the trade-offs between the technological and economic dimensions it embodies) but it might prove impossible to compare *ex ante* two different technological paradigms and even *ex post* there might be overwhelming difficulties in doing it on solely technological grounds. [37]

We tried to suggest some interacting mechanisms between technological factors and economic factors, the latter performing as selective criteria, as final ("market") checking and as a continuous form of incentives, constraints and "feed-back" stimuli. The evidence on market-induced innovative activity (see Schmookler [37]) which survives a closer scrutiny of its empirical foundations [38] may indeed be consistent with our model: economic growth and transformation of the economy involves a permanent re-allocation of resources as well as of research efforts among different sectors, and it is plausible to assume that a greater effort will be put into those areas which offer relatively higher growth and profit opportunities (although the two might not necessarily coincide). This process, however, relates much more to *normal* technology than to discontinuous technological advances. In other words: suppose there are two sectors, both defined by rather stable technological trajectories, which allow broadly similar possibilities of technological advance, [39] but one experiences higher rates of growth of demand than the other. It is plausible that a firm will put greater research efforts into the first rather than the second sector. Moreover, if there is some relationship between research input and innovative output, one may find a higher number of technical innovations (as measured, say, by patents) in the former sector. This induced effect, however, does *not* explain the emergence of significantly radical innovations, which is precisely what one tried to do above. This is not to say that the emergence of new technological paradigms is independent of the evolution and the changes in the social system (of which the economic structure is a crucial component). A reconstruction of the history of technology and history of science would almost certainly show the long-run influences of the evolution of the social and economic structure upon the emergence of new scientific and technological opportunities. Simply, what we want to stress is their relative autonomy vis-a-vis short-run adjustment and inducement mechanisms of the economic system (changes in prices, quantities, profitabilities, etc.).

Various hypotheses on the determinants and directions of technical changes have been proposed, during the past two decades, in a revived attention to the schumpeterian problematique of the long-run relationship between technical change and economic growth (one should actually refer also to Marx as the other classical economist who focussed on the issue). It is worth mentioning these models and hypotheses, not only to acknowledge our theoretical debts, but also to discuss briefly the reciprocal consistency. We refer in particular to Freeman [18], Nelson and Winter [24–26], Rosenberg [30], Abernathy and Utterback [1], Sahal [34 and 7]. In different ways, and with different analytical aims, one may consider these contributions as part of a painstaking attempt to construct a non-neoclassical theory of technical change capable of giving a satisfactory account of (1) the relationship between economic forces and the relatively autonomous momentum that techni-

[37] Another example from the semiconductor industry: how could it have been possible to compare in the 1950s the thermionic valve technology and the emerging semiconductor technology? Even *ex post* (i.e. now) when most of the common dimensions (e.g. size and density, speed, costs, energy consumption, etc.) show the striking superiority of semiconductor technology, valves still maintain in some narrow technological dimensions their advantage. Note that we took here one of the most extreme examples of a new clear-cut "superior" technology: in many other cases even an *ex post* comparison between the different technologies may prove rather difficult.

[38] Walsh et al. [46] examine Schmookler's hypothesis of a dependence of innovative activity upon market growth and in the case of chemical innovations find abundant falsifying evidence.

[39] Note that within stable technologies the possibilities of advances (so to speak, the potential rate of technical progress compatible with that technology) might radically differ. A low possibility of further advances and unsolved (or "badly" solved) technical problems might indeed be a stimulus for the search for a new technological paradigm.

cal progress appears to maintain, (2) the role of supply-side factors, (3) the role and effects of technical change in oligopolistic environments, (4) its relationship with company behaviour and organizational structures, (5) the relevance of non-market organizations and first of all of public institutions in shaping the patterns of technical change.

Broadly speaking, the interpretation of the procedures, progresses and shifts in the innovative process proposed here are, in my view, consistent with the approach of the above cited works, for what they have in common. Few features need mention. In particular, the continuity (and partial overlapping) between our hypothesis and Nelson and Winter's models should be clear enough. The existence of technological paradigms, with the attributes one tried to describe, support the existence of "natural trajectories" of technical change suggested by Nelson and Winter. Their models focus primarily on the *endogenous dynamics* of technical progress in oligopolistic environments (and differential innovative success is, in their simulations of the model, one of the main driving forces toward oligopolistic structures). Translated in the definitions used above, their model [24] gives us a fascinating (and rich in terms of firms' behavioural variables) account of the transition to oligopolistic maturity and of the technology-based oligopolistic competition thereafter, upon a given technological path. On the other hand, the weakness of simple market mechanisms (together with the l inadequacies of institutional intervention) in the innovative process are discussed by Nelson in [27].

Two incidental remarks related to economic theory: first, if technological paradigms and technological trajectories prove to be a general case in the modern history of technology, then it becomes more plausible to assume – in terms of "aggregate" technical progress in the economy as defined by input coefficients of production – one discrete (and limited) set of input combinations. Technical change should then be strictly associated with their movement "outward" (using the traditional representation of production functions) along something like a cone, rather than the movement along and of, a smooth curve. Second, this idea of technological paradigms and trajectories bear some relevance within the revived discussion concerning the existence and the determinants of Kondratief's long-waves (see Clark, Freeman and Soete [6]). One of the variables affecting long-run cycles of capitalist development may be the *establishment* of broad new technological trajectories, which could explain the "clustering" of groups of innovations and, even more important, the "clustering" in time of their economic impact.

The innovative process – both in its "normal" procedures and in its "extraordinary" breakthroughs – is shaped by the interplay of economic and institutional factors. One can distinguish, however, the role of public policies related to the search for new technological paths, from that aimed at technological advances along a broadly defined technology. In the former case policies concern what one may call "the burden of the first comer". Throughout the process of selection and emergence of new technologies, three crucial institutional factors appear to be crucial: (1) the accumulation of knowledge in both "scientific" and "applied" forms (in this respect the existence of "bridging institutions" between proper "science" and technology is of the utmost importance (see Freeman [12]).); (2) forms of institutional intervention which allow "a hundred flowers to blossom and a hundred schools to compete" – both in terms of technological explorations and manufacturing attempts; (3) the selective and focussing effect induced by various forms of *stricto sensu* non-economic interests (such as, for example, military technological requirements and procurement, specific energy saving programmes, the national drive toward self-sufficiency in a particular sector, etc.). One must notice that even when technological paths are well established, the above-mentioned variables may contribute to shape and determine the rate at which technical advances occur. Moreover, even at this stage when technical advances are in many ways endogenous to the economic dynamics, both the uncertainty related to the R&D process and the existence of untraded aspects of technical change do not disappear. Under these circumstances even traditional economics suggest normatively some form of public intervention to correct what it calls "market failures" related to differences between social and private rates of return and between social and private discounts of risks, and to "externalities".

A particularly interesting case refers to countries lagging behind vis-a-vis the technological frontier on a certain technology. If technical advances maintain their cumulative (although stochastic) nature, and if oligopolistic structures tend to appropriate those technological leads, the process of technical change as such is not likely to yield to convergence between countries starting from different technological levels.[40] Imitative technological policies in this case might not be sufficient and public intervention aimed at catching-up might have to affect trade flows, foreign investment, and the structure of the domestic industry (I discuss at some length those policies in Europe and Japan for electronics in [8]).

I wish to make our final comment on the heuristic capability of this interpretation of the process of technical change and innovation. For our suggestion to prove useful, one should be able to (1) identify with sufficient precision the "dimensions" which characterize each broad technological paradigm and differentiate it from others, (2) separate the periods of "normal" technology from extraordinary search, (3) define the "difficult puzzles" and unsolved difficulties of a technology which are often a necessary (although not sufficient) condition for the search for other ones; (4) describe the transition from one technological path to another and assess the factors which allow the emergence of a "winning" technology. Probably this exercise will be possible in some instances and not in others.

Technological paradigms and trajectories, are in some respects metaphors of the interplay between continuity and ruptures in the process of incorporation of knowledge and technology into industrial growth: the metaphor, however, should help to illuminate its various aspects and actors and to suggest a multi-variables approach to the theory of innovation and technical change.

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