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Working Paper Series

Technology and the Economy

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2002/18 **August 2002**

First Draft **August 2002**

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Abstract

The paper, as such a draft of a chapter for the second edition of the *Handbook of Economic Sociology*, Edited by Neil J. Smelser and Richard Swedberg), is meant to offer some sort of roadmap across a few fields of investigation concerning the relationships between technological learning and economic dynamics. Within this broad critical endeavour, one discusses some of the interpretative achievements stemming from e.g. the economics of innovation, industrial economics, epistemology of knowledge, economic sociology and history of technology among others. In particular, one tries to identify the drivers of technological change, possible invariances in the processes of change themselves, their social and institutional roots and some properties of the dynamic coupling between technological learning, forms of corporate organization and economic evolution.

Keywords

Innovation, Technological paradigms, trajectories, organizational capabilities, institutional embeddedness, co-evolution.

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Prepared for the Second Edition of the Handbook of Economic Sociology, Neil J. Smelser and Richard Swedberg editors, 2002.
The chapter draws upon other works by one of the authors - in particular Cimoli and Dosi (1997), Dosi, Freeman and Fabiani (1994) and Dosi (1997) - to which the reader is referred for more detailed discussions.

Introduction

In this chapter we address some general properties of technological change and its co-evolutionary patterns with the economic and social contexts in which it occurs.

Of course it would be a futile enterprise to attempt to survey in a single chapter all the facets of the relationships between the "modern Prometheus" of technological innovation - as David Landes puts it -, on the one hand, and economic development, on the other. Rather, we confine ourselves to some of those aspects of such relationships with straightforward bearings on social embeddedness - to use Granovetter's (1985) fortunate expression - of the process of generation of "useful knowledge" and its economic exploitation.

Admittedly we shall undertake such an exercise from an evolutionary economics perspective: diverse discussions of such a broadly defined research program may be found in Nelson and Winter (1982), Hodgson (1993), Metcalfe (1998), Dosi and Winter (2002), Nelson and Winter (2002), Coriat and Dosi (2000). For our purposes here, let us just emphasize the overlappings between "evolutionary" and a few "socio-economic" interpretations of the fabrics and changes of both technological knowledge and economic structures. Telegraphically, they all share microfoundations grounded on heterogeneous agents, multiple manifestations of "bounded rationality", diverse learning patterns and diverse behavioral regularities (much more on that in Dosi, Marengo and Fagiolo (1996)). At the same time, social embeddedness entails also the long-lasting influences of socio-economic factors upon the rates and directions of accumulation of technological knowledge.

In this respect intricate puzzles concern "what ultimately determines what...": e.g. is resource accumulation that primarily fosters the exploration of novel innovative opportunities, or, conversely, does innovation drive capital accumulation? Do new technological opportunities emerge mainly from some extra economic domain ("pure science") or are they primarily driven by economic incentives? Or are they crucially molded by social interests and politics? Should one assume that the institutions - however defined - supporting technical change are sufficiently adaptive to adjust to whatever economic inducement emerges from market interactions; or, conversely, are they inertial enough to shape the rates and directions of innovation and diffusion?

A first issue that we shall address in the following concerns the identification of possible invariances in the patterns of technological search and knowledge accumulation, together with discrete differences across sectors and industries.

Relatedly, second, a general question regards what one may call the degrees of plasticity of technological changes vis-à-vis economic and social drivers as distinct from the inner momentum that technology-specific opportunities happen to provide. Pushing it to caricatural extremes, what are the constraints to what "money can buy"? And, conversely, are there hard "natural" boundaries to what social dynamics may "negotiate"?

In any case, third, we shall argue that the revealed economic impact of technological innovation crucially depends upon some sorts of combinatorics, entailing "matching"/"mismatching" patterns between: a) the opportunities and constraints offered in any given period by the major available technologies; b) the structures and behaviors of business firms and c) the characteristics of broader institutions governing e.g. labor-, finance- and product-markets.

Our discussion shall begin with a brief overview of some fundamental "stylized facts", that is relatively robust historical regularities at different level of observation - from the very micro to broad societal ones - which motivate interest in the relationships between technological and economic change and also highlight some interpretative puzzles. Next, we shall offer our interpretation of the structure and dynamics of technological knowledge and tackle a few related debates including those impinging on the degrees of embodiment of technological knowledge within business organization; the role of "information" as distinct from "knowledge" stricto sensu; the importance of incentive such as appropriability, on the one hand, and various other social processes, on the other, in driving the rates and directions of technological innovation. Finally the last part of the chapter shall address more explicitly "macro" issues regarding some conjectural properties of the mentioned "combinatorics" between technology, economic structure and institutions.

References in the following to somewhat arcane debates amongst economists of different breeds shall be kept to a minimum (with the inevitable downside of a bias toward the specific authors' interpretative perspective). But fruitful interactions with economic sociology might hopefully be enhanced.

Some stylized facts on Technology and Economic Dynamics

Technical change, economic growth and international trade

- Since the Industrial Revolution a highly skewed international distribution of innovative activities has emerged, starting from rather homogeneous conditions at least between Europe, China and the Arab world (Cipolla 1965).

Table 1 provides a highly impressionistic but revealing picture of the international distribution of innovations from 1750. Although there is probably some Anglo-American bias in the data, a similar pattern is revealed by long-term patenting activities (see Dosi et al. 1990): Innovation appears to be highly concentrated in a small group of industrialized countries (Table 2). The club of major innovators has been quite small over the whole period of around two centuries and half with both restricted entry (with Japan as the only major entrant in the 20th century) and a secular pace of change in relative rankings.

- At the same time, since the Industrial Revolution one observes the explosion of diverging income patterns, starting from quite similar pre-industrial per capita levels. Bairoch (1981, p.5) presents estimates showing that before the Industrial Revolution the income gap between the poorest and the richest countries was certainly smaller than the ratio 1 to 2 and probably of the order of only 1 to 1.5. Conversely, the dominant tendency after the Industrial Revolution is one with fast increasing differentiation among countries and overall divergence (see Bairoch (1981), pp7-8 for evidence). Even in the post World War II period, commonly regarded as an era of growing uniformity, the hypothesis of global convergence (that is convergence of the whole population of countries toward increasingly similar income levels) does not find support from the evidence (De Long 1988; Easterly et al. 1992; Verspagen 1991; Soete and Verspagen 1993; Durlauf and Johnson 1992; Quah 1996). Rather, one finds some - although not overwhelming - evidence of local convergence, i.e. within subsets of countries grouped according to some initial characteristics such as income levels (Durlauf and Johnson 1992) or geographical locations. Still, across-groups differences in growth performances appear to be striking high.
- A delicate but crucial issue concerns the relation between patterns of technical change and patterns of economic growth. Of course, technological learning involves many more elements than simply inventive discovery and patenting: equally important activities are imitation, reverse engineering, adoption of capital-embodied innovations, learning by doing and learning by using (Freeman 1982; Dosi 1988; Pavitt 1999). Moreover, technological change goes often together with organizational innovation. Still, it is important to notice the existence of significant links between innovative activities (measured in a rather narrow sense, i.e. in terms of patenting and R&D activities) and

GDP per capita (for the time being we shall avoid any detailed argument on the direction of causality).

- As discussed in Dosi, Freeman and Fabiani (1994) evidence concerning OECD countries appears to suggests that the relationships between innovative activities and levels of GDP has become closer over time, and is highly significant after World War II. Moreover, innovative dynamism, expressed by the growth of patenting by different countries in USA always appears positively correlated with per capita GDP growth. The link is particularly robust between 1913 and 1970. (Conversely a sign that the regime of international growth might have changed in the 1970s is that in this period the relation gets weaker and loses statistical significance).
- In general, at least since World War II, the rates of growth of GDP appear to depend on (i) domestic innovative activities, (ii) the rates of investment in capital equipment and (iii) international technological diffusion (Fagerberg 1988; De Long et al. 1991; Meliciani 2001).
- In turn, capability of innovating and quickly adopting new technologies are strongly correlated with successful trade performance (Dosi et al. 1990).
- Moreover, despite technological diffusion is taking place at a rather high rates, at least among OECD countries, important specificities in "national systems of innovation" persist related to the characteristics of the scientific and technical infrastructure, local user-producer relationships and other institutional and policy features of each country (Lundvall 1988; 1992; Nelson 1993; Archibugi, Howells and Michie 1999).

Firms, industrial structures and dynamics

- In contemporary economies business firms are a fundamental locus of technological accumulation. This is revealed also by the (high and growing) shares of the total domestic Research and Development they undertake (see figure 1 on US evidence). However the directions and the rates at which they learn vary a lot depending the sectors in which they operate and, relatedly, on the technologies they access (Pavitt 1984; Levin, Cohen and Mowery 1985; Dosi 1988; Freeman 1994; Freeman and Soete 1997).

- In any case, neither the secularly growing importance innovative search internalized within firms, nor the more recent ability by the latter to utilize "artificial" exploration and design technologies - from CAD to simulation models - has eliminated the intrinsic uncertainty associated with the innovation process. Trials and errors, unpredictable failures and unexpected successes continue to be a general feature of technological innovation in contemporary economies.
- And so continue to be the persistence of systematic differences across firms, even within the same lines of activities, in innovative abilities, production efficiencies, profitabilities: i.e. what in a short hand are called elsewhere (Dosi 1988) asymmetries across firms. For evidence, amongst many others, see Davies, Haltiwanger and Schuh (1996); Baily, Hulten and Campbell (1992); Baldwin (1995); and the whole special issue of Industrial and Corporate Change. A striking illustration of a much wider phenomenon is the dispersion of labor productivities even within the same sectors of activity and under roughly the same relative prices. See figure 2 for some pieces of evidence from Italy to that effect.
- Industrial structures and industrial change present a few remarkable regularities, too, shared by most industrialized countries. Variables like capital intensity, advertising expenditures, R&D and patent intensities, concentration, profitability, firms' entry exit and survival rates remarkably differ across sectors while presenting high cross country similarities. Moreover, specific industries display rather similar characteristics, in terms of industrial dynamics in different countries. Finally, both industrial structures and dynamics appear to be profoundly shaped by the nature of the technologies upon which

individual industries draw (Pavitt 1984; Dosi 1988; Dosi et al. 1995; Breschi, Malerba and Orsenigo 2000; Marsili (2001) and the evidence cited therein).

How does one interpret the bulk of the foregoing evidence? For example, why technological learning appears, at least at a first look, to be both a driver of economic growth but also a factor of divergence across countries and even across firms? More generally, how does one link any story primarily focused upon the dynamics of knowledge with another one wherein the primary actors are business firms, products, markets, etc. and with yet another one primarily featuring non- market institutions?

In order to begin to address these questions, let us try to characterize the nature of technology and technological innovation, as we see it.

Knowledge, Technology and innovation: some basic features

Technological paradigms and trajectories

A variety of concepts have been put forward over the last couple of decades to define the nature of innovative activities[1]: technological regimes, paradigms, trajectories, salients, guidepost, dominant design and so on. The names are not so important (although some standardization could make the diffusion of ideas easier!). More crucially, these concepts are highly overlapping in that they try to capture a few common features of the procedures and direction of technical change. Let us consider some of them.

The notion of technological paradigm which shall be for the time being our yardstick is based on a view of technology grounded on the following three fundamental ideas.

First, it suggests that any satisfactory description of 'what is technology' and how it changes must also embody the representation of the specific forms of knowledge on which a particular activity is based and can not be reduced to a set of well-defined blueprints. It primarily concerns problem-solving activities involving - to varying degrees - also tacit forms of knowledge embodied in individuals and organizational procedures.

Second, paradigms entail specific heuristic and visions on "how to do things" and how to improve them, often shared by the community of practitioners in each particular activity (engineers, firms, technical society, etc.), i.e. they entail collectively shared cognitive frames (Constant 1980).

Third, paradigms often also define basic templates of artifacts and systems, which over time are progressively modified and improved. These basic artifacts can also be described in terms of some fundamental technological and economic characteristics. For example, in the case of an airplane, their basic attributes are described not only and obviously in terms of inputs and production costs, but also on the basis of some salient technological features such as wing-load, take-off weight, speed, distance it can cover, etc. What is interesting here is that technical progress seems to display patterns and invariances in terms of these product characteristics. Similar examples of technological invariances can be found e.g. in semiconductors, agricultural equipment, automobiles and a few other micro technological studies (Sahal 1981; Grupp 1992; Saviotti 1996). Hence the notion of technological trajectories associated with the progressive realization of the innovative opportunities underlying each paradigm - which can in principle be measured in terms of the changes in the fundamental techno-economic characteristics of artifacts and production processes[2]. The core ideas involved in this notion of trajectories are the following.

First, each particular body of knowledge (each paradigm) shapes and constraints the rates and direction of technical change, in a first rough approximation, irrespectively of market inducements. Second, technical change is partly driven by repeated attempts to cope with technological imbalances which itself creates[3]. Third, as a consequence, one should be able to observe regularities and invariances in the pattern of technical change which hold under different market conditions (e.g. under different relative prices) and whose disruption is mainly correlated with radical changes in knowledge-bases (in paradigms).

Table 3, showing the so called Moore's law - the steady exponential increase in transistor-per-chip and clock speed in microprocessors - is just the most famous examples among many others.

Moreover a rather general property, by now widely acknowledged in the innovation literature, is that learning is local and cumulative. "Locality" means that the exploration and development of new techniques and product architectures is likely to occur in the neighborhood of the techniques and architectures already in use (Atkinson and Stiglitz 1969; David 1975; Antonelli 1995). "Cumulativeness" stands for the property that current technological developments often build upon past experiences of production and innovation, proceed via sequences of specific problem solving junctures (Vincenti 1990), and in a few circumstances also lead to microeconomic serial correlations in successes and failures. This is what Paul David citing Robert Merton citing The New Testament calls the Matthew Effect: "For unto every one that hath shall be given, and he shall have abundance: but from him that hath not shall be taken away even that which he hath" (Merton 1968, p.3). Note that "cumulativeness" at micro level provides robust support for those interfirm asymmetries mentioned earlier, while industry-wide, region-wide and country-wide factors of cumulativeness in learning dynamics are good candidates to the explanation of why industries, region and countries tend to systematically differ in both technological and economic performances.

The robustness of notions such as technological trajectories or similar ones is of course a primarily empirical question. Come as it may, fundamental issues regard the carriers, the fine grained processes and the driving factors underlying the observed patterns of technological change.

Our discussion so far has primarily focused upon some general features of technological knowledge and its revealed techno-economic outcomes (we shall come back below to some further properties of knowledge accumulation as such). However, a good deal of "economically useful" technological knowledge is nowadays mastered by business firms, which even undertake in some countries - such as the USA, Nordic European countries, Germany and few others - a small but not negligible portion of the effects aimed at a more speculative understandings of physical, chemical, biological properties of our world (i.e. they also undertake "basic science")[4]. How does all that relate with the structure and behaviors of firms themselves?

Knowledge, routines and capabilities in business organizations

Possibly one of the most exciting, far from over, intellectual enterprises developed over the last decade has involved the interbreeding between the evolutionary economics research program, (largely evolutionary inspired) technological innovation studies and an emerging competence-/capability-based theory of the firm. The roots rest in the pioneering organizational studies by Herbert Simon, James March and colleagues (Simon 1969; March and Simon 1993; Cyert and March 1992; March 1988) and in the equally pioneering explorations of thee nature and economic implications of organizational routines by Nelson and Winter (1982) (with the follow-ups such as those discussed in Cohen et al.(1996); Teece, Pisano and Schuen (1997); Dosi, Nelson and Winter (2000); Dosi, Coriat and Pavitt (2000); the Special Issue of Industrial and Corporate Change, 2000, edited by Mie Augier and James March; Montgomery (1995); and Foss and Mahnke (2000)). It is familiar enough to most readers (nowadays even to a few economists!) that business firms "know how to do certain things" - things like building automobiles and computers - and know that with different efficacies and revealed performances. In turn, as one discusses in Dosi, Nelson and Winter (2000) and Dosi, Coriat and Pavitt (2000) what does "organizational knowledge" mean? What are the mechanisms that govern how it is acquired, maintained and sometimes lost? As we suggest in the just cited works, organizational knowledge is in fact a fundamental link between the social pool of knowledge / skills / discovery opportunities, on the one hand, and the rates / direction / economic effectiveness of their exploration / development / exploitation on the other.

Distinctive organizational competences/capabilities[5] bear their importance also in that they persistently shape the destiny of individual firms - in terms of e.g. profitability, growth, probability of survival - and, at least equally important, their distribution across firms shapes the patterns of change of broader aggregates such as particular sectors or whole countries.

"Competences" and "capabilities" build on ensembles of organizational routines. In turn, the latter (i) as thoroughly argued by Nelson and Winter (1982), embody a good part of the memory of the problem-solving repertoires of any one organization: (ii) entail complementary mechanisms of governance for potentially conflicting interests (for a more detailed discussion see Coriat and Dosi (1988b)), and, (iii) might well involve also some "meta-routines", apt to painstakingly assess and possibly challenge and modify "lower level" organizational practices (in that, R&D activities as well, often, recurrent exercises of "strategic adjustment" are good cases to the point).

In this view, routines and other recurrent organizational practices may be interpreted as a set of problem-solving procedures in turn composed of elementary physical acts (such as moving a drawing from an office to another or doing an operation on a machine tool) and elementary cognitive acts (such as doing a certain calculation).

As one argues in Dosi, Hobday, Marengo and Prencipe (2002) it is helpful to think of complex problem solving activities as problems of design: the design of elaborate artifacts and the design of the processes and organizational structures required to produce them. These processes require the design of complex sequences of moves, rules, behaviors and search heuristics typically involving multiple actors. In turns the patterns of knowledge decomposition contribute to shape (but are far from identical to) the division of labor within and across organization (more in Marengo et al. (2000), Teece et al. (1994), Dosi, Hobday and Marengo (2000)).

The general conjecture of many evolutionary economists is indeed that by opening up, together, the "technological blackbox" and the "organizational blackbox" one is likely to find robust mappings between the patterns in the collective distributions of technological knowledge and the properties of organizational structures and behaviors. We shall come back below to some historical examples. Here, in any case, notice a major domain of interaction between (evolutionary) economics, organization theory and economic sociology - largely waiting to be explored.

The "anatomy" of regimes of knowledge accumulation and their sectoral dimensions

Another largely unexplored field of inquiry is the exploration of technology-specific patterns of knowledge accumulation - of which, an early largely cited prototype is Pavitt (1984) - attempting to study the diversity of innovation patterns across industrial sectors and identify taxonomies of technological regimes. Such regimes are based on industry-specific properties of search for technological improvements and on specific natures and sources of knowledge-bases. In line with taxonomic exercise such as Pavitt (1984), Patel and Pavitt (1997), Breschi, Malerba and Orsenigo (2000), Marsili (2001) the inquiry builds on three basic conjectures, namely that, first, notwithstanding the importance of country-wide institutional factors, the properties of innovation processes are, to a significant extent, invariant across countries and specific to technologies or industrial sectors; second, some general properties of innovation processes shared by populations of firms might be identified independently of a variety of idiosyncratic behaviors identifiable at firm-level; and third, diverse regimes entail different technological entry barriers, stemming from diverse mode of access to novel opportunities by entrants as opposed to (cumulatively learning) incumbents (Marsili 2001). Again, it could well be at this junction between industrial economics, economic sociology, and the sociology of knowledge that one might fruitful address a few of the apparent puzzles, briefly mentioned above, concerning the determinants of observed industrial structures and their changes.

Information and knowledge in technology and innovation

That there is more to technology and innovation than sheer "information" is not likely to be big news to social scientists (except possibly economists!) and practitioners alike.

However, one can go already a long way be rigorously exploring the economic properties of information as such (and in any case technological activities involve a rich information content). Building on the pioneering works of Simon (1951), Arrow (1962), Nelson (1962), Akerlof (1984), Greenwald and Stiglitz (1986), Radner (1992), Aoki (1990) among a few other distinguished authors, it is easy nowadays to acknowledge some fundamental economic specificities of "information" as such.

For example, in many respects similar to that of a "public good" - in many economists jargon -, the use of information is

- non-rival (the fact that one uses it does not prevent the others from using it too);
- non-excludable (were it not for institutional provisions such as patent-based monopoly rights of exploitation).

Moreover, its generation is subject to:

- sunk, upfront, costs of production and basically zero cost of reproduction (in an illustrative caricatures, the "cost of production" of Pytagoras Theorem has been fully born by Pytagoras himself, while we can infinitely re-use it at our will; near to our concerns the same applies to e.g. software);
- if anything, there are increasing returns to its use, in the sense that the more we use it the easier it is, and, dynamically, the higher is the likelihood of learning and producing ourselves "better", "novel", in some sense "innovative" further pieces of information.

As already mentioned far reaching conclusions can be reached by just seriously exploring the economic implications of different distributions and processes of generation of information. Consider for example the path-breaking works by Masahiko Aoki on the properties of different distributions of information in the comparison between archetypichal "Japanese" and "American" firms (Aoki 1990). Another example are the painstaking investigations of the conditions for the existence of "markets for technologies" (Arora, Fosfuri and Gambardella 2001).

More generally, note that the very properties of information mentioned above most often entail phenomena of market failures (as marginal prices are of no guidance to efficient market allocation and equilibria might even fail to exist): see Stiglitz (1994) for a through discussion with far reaching interpretative and political implication.

Having saying that, further insights may be gained by distinguishing between sheer information and knowledge. As one discusses at greater length in Dosi, Marengo and Fagiolo (1996), the former entails well stated and codified propositions about (i) states-of-the world (e.g. "it is raining?"), (ii) property of nature (e.g. "A causes B?"), (iii) identities of other agents ("I know Mr. X and he is a crook?") and (iv) explicit algorithm on how to do things[6]. Conversely, knowledge, in the definition we propose here, includes (i) cognitive categories; (ii) codes of interpretation of the information itself; (iii) tacit skills, and (iv) search and problem-solving heuristics irreducible to well defined algorithms.

So, for example, the few hundred pages of demonstration of the last Fermat theorem would come under the heading of "information". Granted that, only some dozens mathematician in the world will have the adequate "knowledge" to understand and evaluate it. On the other hand, a chimpanzee, facing those same pages of information might just feel like eating them, and the vast majority of humans being would fall somewhere in between these two extremes. Similarly a manual on "how to produce microprocessors" is "information", while knowledge concerns the pre-existing ability of the reader to understand and implement the instruction contained therein.

Moreover, in this definition, knowledge includes tacit and rather automatic skills like operating a particular machine or correctly driving a car to overtake another one (without stopping first in order to solve the appropriate system of differential equations!).

And, finally it includes "visions" and ill-defined rules of search, like those involved in most activities of scientific discovery and in technological and organizational innovation (e.g. proving a new theorem, designing a new kind of car, figuring out the behavioral pattern of a new kind of crook that appeared on financial market?).

In this definition, knowledge is to varying degree tacit (Polanyi 1966; Nelson and Winter 1982) at the very least in the sense that the agent itself, and even a very sophisticated observer, would find it very hard to explicitly state the sequence of procedures by which information is coded, behavioral patterns are formed, problems are solved, etc. Incidentally note also that even in scientific activities tacit knowledge plays an important role: as recognized by sociologists like Collins (1974) and Callon (1995), the "knowledge" used and diffused cannot be reduced to fully explicit codified statements (i.e. information) but involves personal interactions, observation and practical experience in specific contexts.

On the ground of these distinction, one may look again at the puzzles implied by the empirical evidence discussed earlier and ask, with Pavitt, questions like:

> "If knowledge is costless to transmit and re-use why can't foreigners - who have not paid for research - benefit from it (the free rider problem)? If the cost of obtaining foreign produced knowledge is negligible, why do many small countries in North-Western Europe perform relatively more basic research than the USA itself??Why do firms in science-based industries extensively publish the results of their research when, according to the information based view of knowledge, they should be appropriating them by keeping them secret or protecting them through patents??" (Pavitt 2002, p.7).

We fully share also Pavitt's answer: the apparent anomalies melt away if one acknowledges the tacit aspect of knowledge, intimately complementary to codified information, person- or organization-embodied, and rather sticky in its transmission (Pavitt 2002).

Not all the analysts of technology however share this view. A few scholars argue indeed that the notion of tacitness has been overrated and that the "degrees of tacitness" ultimately depend upon the cost and benefits involved in the process of articulating and codifying knowledge rather than upon some intrinsic properties of knowledge itself (see Cowan, David and Foray (2000) and the whole special issues of Industrial and Corporate Change (2000) edited by Cohendet and Steinmuller, devoted to the subject). The question, in this alternative view, ultimately boils down to a matter of incentives and availability of new technologies - today, in primis, information and communication technologies (ICT) - apt to facilitate the codification job.

Here of course we are far from denying that a massive process of knowledge codification is in progress, indeed fostered by ICT's and reaching domains previously ruled by tacitness - from artifacts design to a few control and production activities previously unaffected by forms of electromechanical automation (Balconi 1998).

However, we maintain, tacit features of knowledge continue to be an intrinsic part of technical change and they are also essential to the very process of codification and to the attribution of meaning to information itself. Moreover we suggest, quite irrespectively of any incentive, the nature of specific knowledge bases deeply influence the degrees of difficulty in codification (or indeed its sheer impossibility: for example it can be formally proved that no codified process can be established ex ante in order to prove yet undemonstrated theorems; by the same token in the technological domain it is hard to think of a codified process able to develop what we do not know yet?). Together, our general conjecture here is that the diverse degrees to which knowledge bases can be easily codified contributes to explain also the "uneven development of human know-how"[7] in different fields.

The tangled relationships between sciences and technologies

There is little question that science plays a crucial role in opening up new possibilities of major technological advances. The linkages between science and technology have been tight ever since the rise of modern science[8] but, especially in this century, the emergence of major new technological paradigms has frequently been directly linked with major scientific breakthroughs. Until the end of the nineteenth century, technological innovations were typically introduced by imaginative craftsmen - typical examples being the development of engines by practical-minded inventors well before the works of Carnot on thermodynamics or the invention of the chronograph for measuring longitude by the watchmaker John Harrison in 1730 against the opinion of the astronomers including Halley (Sobel 1996). Conversely, in this century, as far as major innovations are concerned, one moves closer to a science-based model of technological innovation. Important instances in this respect are the origin of synthetic chemistry (Freeman 1982) and the transistor (Nelson 1962; H. S. Kleiman 1977; Dosi 1984). For example, in the latter case the discovery of certain quantum mechanics properties of semiconductors, yielding a Nobel Prize for physics, and the technological development of the first microelectronics device have been one and the same thing (Nelson 1962; Braun and MacDonald 1978; Dosi 1984). In more recent years, one finds many further examples, the extreme one being probably biotechnology and more generally life-sciences (Orsenigo 1988; Henderson et al. 1999). Other instances, include computational chemistry and speech-recognition (Koumpis and Pavitt 1999, Mahdi and Pavitt 1997), just to name a few.

The increasing role of scientific knowledge in technological advances as gone together with major changes in the overall organization of innovative activities.

The conventional way of representing the impact of science on technological innovation has been often captured by some version of the (improperly called!) "Arrow-Nelson model" (Arrow 1962; Nelson 1959 and 1982; see also David, Mowery and Steinmueller (1992)), whereby (exogenously determined) science provides the pool of notional opportunities upon which industrial R&D, and more generally "technologically useful" knowledge, draws.

It is indeed a useful first approximation, but we cannot stop there and must thereafter acknowledge that the relationship between science and technology goes both ways. As discussed in Rosenberg (1982) and (1994), Freeman and Soete (1997), Pavitt (1999), Brooks (1994), factors of influence of scientific knowledge on technology include:

- of course, the knowledge new "properties of nature" upon which technologies can build upon;
- the development of new design tools and instruments initially aimed at scientific research which are thereafter applied to commercial uses - examples among many being

the Scanning Electron microscope, the laser and many others (Rosenberg 1990; Brooks 1994).

- Training of applied researchers mastering state-of-the-art scientific knowledge.

Conversely, technology has contributed to science:

- as a source of new scientific challenges (Brooks 1994);
- with new instrumentation and measurement technologies needed to address novel scientific question more efficiently.

Indeed the accumulation of technical knowledge has provided for centuries a base of observations that subsequently stimulated and focussed scientific research (see Rosenberg (1982) for a thorough discussion)[9].

Similarly, the development of instrumentation has exerted a major impact on subsequent scientific progress: just think of the microscope, the telescope, x-ray crystallography and obviously the computer. More generally, the allocation of resources to specific scientific fields is often strongly influenced by prior expectations on technological payoffs as well as by the nature and the interests of the "bridging institutions"[10] that are instrumental in applying theoretical advances to the development of practical devices even under remote or nonexistent direct economic incentives (this is the case of public agencies like the military[11]).

Incidentally note also that in recent years, the increased closeness of scientific research and technological innovation in fields like biotechnology and information technology, jointly with an increasing involvement of scientific institutions in commercial activities is leading to the concern that scientific research runs the risk of becoming too dependent and hostage of immediate and direct economic interests, thereby compromising the ethos of science that has proved so beneficial to the society and the economy (Dasgupta and David 1994; Mazzoleni and Nelson 1998). We shall briefly come back to this issue below.

In most contemporary developed economies, one typically observes quite a few institutions, together with a multitude of profit-seeking firms, sharing in different combinations the tasks of scientific explorations and search for would-be technological applications[12]. However the relevance of scientific knowledge and the mechanisms through which such knowledge is transmitted vary greatly across scientific disciplines, technologies and industries (Rosenberg and Nelson, 1994). Various studies (Mansfield 1991; Jaffee 1989; Jaffee, Trajitenberg and Henderson 1993; Audretsch and Feldman 1996; Klevorick et al. 1995) have shown that science is directly relevant to industrial R&D only in a small number of industries - typically, agriculture, chemicals and pharmaceuticals, electronics, precision instruments). Some scientific disciplines - like mathematics and physics - are relevant for an very large variety of industries, but mostly in an indirect way. Others - e.g. biology - have a more immediate practical impact, which is however concentrated in a small spectrum of industries. In general, however, the evidence seems to support the notion that science is indeed a crucial component of industrial innovation as an ingredient that increases the "general and generic" ability to solve complex technical problems (Mansfield 1991; Klevorick et al. 1995).

Historically, the contemporary symbiotic relationship between activities of scientific and technological came about through two converging processes. A first one involved the progressive incorporation of R&D activities within business firms, beginning in the late 19th centuries in few countries - like Germany, Switzerland, and a bit later the USA - and few sectors - notably chemicals and heavy electrical engineering. Along with the institutionalization of industrial R&D within "Chandlerian" firms, second, the institutionalization of academic research proceeded too, albeit at a very different pace and with large differences across countries.

In the USA, as Rosenberg and Nelson (1994) have pointed out, before War Word II, the linkages between academic and industrial research were frequent but not always systematically organized. Despite some debate among historians, it is usually recognized that the quality of American academic science was by and large lagging behind Europe, with some important exceptions like chemistry and biology (Cohen 1976; Thackray 1982, Mowery and Rosenberg 1998). However, universities developed quickly relatively strong interactions with industry, especially at the local level in response to practical concerns and particularly in practically oriented disciplines - like engineering, medicine, agricultural sciences, etc.. Until World War II, this was actually the main function that - jointly with teaching - universities performed in favor of business firms. Similarly, Mowery and Rosenberg (1998) have argued that the contributions of American University research to economic growth were not only the product of a few elite universities, but involved many universities, many of them providing local service to local industry and agriculture.

The explosive growth of investment in scientific research - mainly coming from public sources and mainly directed to universities and other public research institutions - marks a distinct feature of the economic development of most industrial countries in the post War World II era. And it also marks the quick emergence of a long lasting American leadership regarding both quite a few scientific disciplines and most "frontier" technologies.

In a nutshell, all developed contemporary economies - notwithstanding important national specificities - share mechanisms of generation and exploitation of innovative opportunities involving the interaction between:

- The continuous accumulation of scientific knowledge (to a good extent exogenous to business firms, but not entirely: to repeat, firms do undertake a significant amount of basic research (Rosenberg 1990; Pavitt 1991).
- Multiple learning process endogenous to individual firms and networks of them entailing: (i) formal R&D activity, but also more informal processes of (ii) learning from design, production and marketing; (iii) learning-by-interacting with customers and suppliers.

As already mentioned the balance between these diverse learning procedures vary across technologies and industrial sectors highlighting a variegated "anatomy" of the capitalistic innovation engine[13].

Having saying that, crucial issues regard the underlying forces driving technological accumulation throughout such a system and in particular the role of economic and social factors.

Economic and social factors in the emergence of new paradigms

It is useful to separate the genesis of new paradigms from the processes leading to the dominance of some of them. Let us first consider the emergence of new potential paradigms; that is generation of notional opportunities of radical innovations involving new knowledge bases, new search heuristics, new dominant designs.

Indeed, there are good reasons to believe that one will not be able to find anything like a general theory of the emergence of new technological paradigms. However, what might be possible is a) an analysis of the necessary conditions for such emergence; b) historical taxonomies and also appreciative models of the processes by which it occurs; and c) taxonomies and models of the processes of competition amongst different paradigms and their diffusions.

Regarding the first heading, one is like to find that the existence of some unexploited technological opportunities, together with the relevant knowledge base and some minimal appropriability conditions, define only the boundaries of the set of potential new paradigms: those which are actually explored within this set might crucially depend on particular organizational and social dynamics. So for example there is good evidence that the microelectronic paradigm as we know it (silicon-based, etc.) was shaped in its early stages by military requirements (Dosi 1984; Misa 1985). David Noble (1984) argues that the NC machine-tools paradigm - although he does not use that expression - has been influenced by power consideration regarding labor management. In the history of technologies one finds several examples of this kind. The general point is that various institutions (ranging from incumbent firms to government agencies), social groups and also individual agents (including of course individual inventors and entrepreneurs) perform as ex ante selectors of the avenues of research that are pursued, the techno-economic dimensions upon which research ought to focus, the knowledge base one calls upon. Thus, they ultimately select the new paradigms that are actually explored.

Conversely, there is a much more general theoretical story regarding the development, diffusion and competition among those (possible alternative) paradigms that are actually explored. It can be told via explicit evolutionary models (as in Nelson and Winter (1982) or in Silverberg, Dosi and Orsenigo (1988)), via path-dependent stochastic models (as in Arthur (1988), Arthur, Ermoliev and Kaniovski (1987), Dosi and Kaniovski (1994)), and also via sociological models of network development (as in Callon (1991)). The basic ingredients of the story are (i) some forms of dynamics increasing returns (for example in learning); (ii) positive externalities in the production or the use if technology; (iii) endogenous expectation formation; (iv) some market dynamics which selects ex post amongst products, and indirectly amongst technologies and firms;

(v) the progressive development of standards and relatively inertial institutions which embody and reproduce particular forms of knowledge and also the behavioral norms and incentives to do so.

Economic Influences upon the patterns of technological changes

Economic factors do influence also the rates and direction of "normal" technical change although within some boundaries set by the nature of each paradigm. The story we propose runs as follows.

Each body of knowledge specific to particular technologies determines in the short term the notional opportunities of "normal" technical advance and also the scope of possible variation in input coefficients, production processes and characteristics of the artifacts in response to changing economic conditions. So, for example the semiconductor-based paradigm in microelectronics or the oil-based paradigm in organic chemistry broadly shape the scope and directions of technical progress - i.e. the "trajectories" - in both product and process technologies (for example, miniaturization and increasing chip density in semiconductors, polymerization techniques in organic chemicals, etc.). In turn, inducement effects can work basically in four ways, operating through (i) changes in search/problem solving heuristics induced by relative prices change and supply/demand conditions; (ii) effects of demand patterns upon the allocation of search efforts across diverse production activities; (iii) the effects of appropriability conditions, again, upon search efforts; and (iv) selection dynamics weeding-out ever-changing "populations" of technologies, artifacts, behavioral traits and firms.

Search Heuristics.

Changes in relative price and demand or supply condition may affect search heuristics, acting as Rosenberg (1976) puts it, as focusing devices: historical illustrations are quite a few cases of supply shocks and technological bottlenecks, from the continental blockade during Napoleon wars to technical imbalances in the late nineteenth century history of mechanical technologies.

Output Growth and Search Efforts.

"Inducement" may take the form of an influence of market conditions upon the relative allocation of search efforts to different technologies or products. In the literature, it has come to be known as the "Schmookler's hypothesis" (Schmookler 1966), suggesting that cross-product differences in the rates of innovation (as measured by patenting) could be explained by differences in the relative rates of growth of demand. Note that, in this respect, while there is no a priori reason why the perception of demand opportunities should not influence the relative allocation of technology efforts, the general idea of "demand-led" innovation has been criticized at its foundations for its theoretical ambiguities (does one talk about observed demand? or expected demand? and how are these expectations formed?) (Mowery and Rosenberg 1979). Moreover, the empirical evidence is mixed. The review in Freeman (1994, p.480) concludes that "the majority of innovations characterized as "demand-led"?were actually relatively minor innovation along established trajectories" while as shown by Walsh (1984) and Fleck (1988), "counter-Schmookler-type patterns was the characteristic of the early stages of innovation in synthetic materials, drugs, dyestuffs.." and robotics (Freeman 1984, p.480).

As emphasized by Freeman himself and by Kline and Rosenberg (1986), the major step forward here is the abandonment of any 'linear' model of innovation (no matter wether driven by demand or technological shocks) and the acknowledgment of a co-evolutionary view embodying persistent feedback loops between innovation, diffusion and endogenous generation of further opportunities of advancement.

Appropriability and Rates of Innovation.

The properties of innovation and knowledge discussed above also entail a fundamental tradeoff powerfully highlighted by Schumpeter (and earlier Marx). Were technological advances (or for that matter technological knowledge) a sheer public good, no incentive would be there for profit-seeking agents to strive for it. Conversely, some expected appropriation of some economic benefit from successful technological implies also systematic departures from the mythical "pure competition" yardstick of which economists are so fond of.

In fact, a few appropriability devices are often at work in contemporary economies including (a) patents, (b) secrecy, (c) lead times, (d) costs and time required for duplication, (e) learning-curve effects, (f) superior sales and service efforts. To these one should add more obvious forms of appropriation of differential technical efficiency related to scale economies and more generally the control of complementary assets and technologies, that are not directly ingredients of the innovation, but allow inventors to extract the profits from it (Teece 1986)[14].

In an extreme synthesis, Levin et al. (1985, p. 33) find that for most industries, "lead times and learning curve advantages, combined with complementary marketing efforts, appear to be the principle mechanisms of appropriating returns for product innovations". Learning curves, secrecy and lead times are also the major appropriation mechanisms for process innovations. Patenting often appears to be a complementary mechanism which, however, does not seem to be the central one, with some exceptions (e. g., chemicals and pharmaceutical products). Moreover, by comparing the protection of processes and products, one tends to observe that lead times and learning curves are relatively more effective ways of protecting process innovations, while patents are a relatively better protection for product innovations.

Moreover, there appears to be quite significant interindustrial variance in the importance of the various ways of protecting innovations and in the overall degrees of appropriability: Some three-quarters of the industries surveyed by the study reported the existence of at least one effective means of protecting process innovation, and more than

90 percent of' the industries reported the same regarding product innovations (Levin et al. 1985, p. 20; these results have been confirmed by a series of other subsequent studies conducted for other countries (see for example the PACE study for the European Union (Arundel, van de Paal and Soete 1995), suggesting that appropriability conditions are rather similar across advanced industrialized countries).

Granted that, highly controversial issues concern the relation between degrees of appropriability, above some minimal threshold, and search efforts by private self-seeking agents. Do innovative efforts grow monotonically in the expectations of rents stemming from would-be innovation? And, more specifically, what is the influence of different patenting regimes and other forms of enforcement of Intellectual Property Right (IPR) upon innovation rates?

One cannot review here a rapidly growing literature whose striking bottom line is however the very little evidence supporting the (misplaced) common wisdom that tighter appropriability regimes unambiguously foster innovative activities.

Historical examples, such as those quoted by Merges and Nelson (1994) on the Selden patent around the use of a light gasoline in an internal combustion engine to power an automobile or the Wright brothers patent on an efficient stabilizing and steering system for flying machines, are good cases to the point, showing how the how the IPR regime probably slowed down considerably the subsequent development of automobiles and aircrafts, due to the time and resources consumed by lawsuits against the patents themselves. The current debate on property rights in biotechnology suggests similar problems, whereby granting very broad claims on patents might have a detrimental effect on the rate of technical change, insofar as they preclude the exploration of alternative applications of the patented invention. This is particularly the case when inventions concerning fundamental techniques or knowledge are concerned, e.g. genes or the Leder and Stewart patent on the achievement of a genetically engineered mouse that develops cancer. This is clearly a fundamental research tool. To the extent that such techniques and knowledge are critical for further research that proceeds cumulatively on the basis of the original invention, the attribution of broad property rights might severely hamper further developments. Even more so, if the patent protects non only the product the inventors have achieved (the "onco-mouse") but all the class of products that could be produced through that principle, i.e. "all transgenic non-human mammals", or all the possible uses of a patented invention (say, a gene sequence), even though they are not named in the application[15].

A further set of problems is exemplified by the celebrated anti-commons tragedy raised by Heller and Eisenberg (1998): while in the commons problem the lack of proprietary rights is argued to lead to over-utilization and depletion of common goods, in biotechnology the risk may be that excessive fragmentation of IPRs among too many owners can slow down research activities because each owner can block each other. (At a more theoretical level, see the insightful discussion by Winter (1993) showing how tight appropriability regimes in evolutionary environments might deter technical progress).

Economic Factors Shaping Selection Process

Evolutionary economists share with evolutionary epistemologists and a few historians of technologies (David, 1975 (putting the past?); Mokyr (2000), Vincenti (1990), Nelson (2003), among others) the view that it is the coupling between some variety-generating mechanism and some selection process that drive technological change. Having saying that, more controversial issues regard (a) the unit of selection, (b) the nature of selection process, and, (c) the criteria driving selection itself.

Concerning the unit of selection, good candidates are:

- technological paradigms and, at a smaller scale, specific technologies and pieces of knowledge;

- artifacts;
- organizational routines;
- firms;

Note that they are not at all mutually exclusive. On the contrary it is plausible to think of diverse processes of selection partially nested into each other and possibly occurring at different time scale. So for example, products markets typically select upon artifacts, affecting only indirectly - via rewards/penalties in terms of profits and markets shares - the selection amongst firms. Financial markets, on the contrary, typically operate upon firms as such. In turn, direct or indirect processes of firm selection ultimately involve a selection among routines and among technologies, in so far as firms are their specific carriers. Moreover, techniques and paradigms also undergo, so to speak "ex-ante" selection processes within firms, communities of practitioners, technical association, universities, etc. involving more explicit, even if still mistake-ridden, deliberative procedures. Illustrative examples are Vincenti's story on aircraft design (Vincenti 1990) and Warglien's account of the hierarchically nested process of project selection within a microelectronic firm (Warglien 2000).

Incidentally, note in this respect that paradigms and dominant designs act at the same time as sources of variation-generation and also of "blindness-reduction" in the generation process itself, without however taking away the intrinsic "stochastic element in what is actually produced, chosen and put to test of use" (Ziman 2000, p.6).

Economic criteria clearly shape, in different ways, the selection criteria of all the foregoing processes. For example, prices and users' revealed preferences straightforwardly influence selection over population of artifacts and so do profitabilities with respect to financial allocation mechanism across firm. And, indirectly, economic influence inform also "ex ante" selection mechanism via the interests and the expectations of all economic actors when "choosing" to explore particular venues of search, particular artifact design, particular problem solving procedures and not others.

But what about strictly social factors? How do they influence the rates and direction of technical change?

The Scope and Bounds of Social Shaping of Technology

It should be abundantly clear from the foregoing discussion that in our interpretation diverse social and political forces play a crucial role, first, in the dynamic of selection amongst would-be paradigms, and, second, in the shaping of the actual trajectories explored within each paradigm. If anything, even such a distinction is somewhat artificial: as Constant (1980) and (1987) shows, just with a slightly different language, paradigms and trajectories emerge together with (i) a technological community, (ii) corporate organizations carriers of such knowledge, and (iii) related technological systems. We have briefly mentioned the co-evolutionary processes linking the dynamics of knowledge, on the one hand, and the dynamics of business organization seen as repositories of problem solving routines, on the other. Yet another, complementary, representation would be in terms of the emergence and establishment of professional communities and related institutions (e.g. the communities of chemicals engineers, their journals, professional societies, university departments, etc.), intimately linked with a broadly shared body of knowledge and practices.

In our view, there is indeed little doubt on the importance of the social shaping of technology, as MacKenzie and Wajcman (1995) put it (see also Rip, Misa and Schot (1995)). However important controversies concern (i) the bounds which the nature of specific technical problems and of specific bodies of knowledge put upon the reach of "battling competing interests and more or less effective campaigns to capture the hearts and minds of (different constituencies)" (Nelson 2003, p.514), and (ii) the degrees of "social re-negotiability" of whatever incumbent technological system (i.e. its lack of path dependency).

A rich and diverse literature, stemming primarily from the sociology of science and technology tackles this issues (see Bijker et al. (1997), and the thorough review in Williams and Edge (1996)). It is impossible to discuss here this line of studies. Let us just admit that we often find many contributions in this vein a bit too near the second extreme of a continuum having on one side naive forms of "technological determinism" (i.e. search and exploration is always about finding objectively better solution to old and new technical problems) and, on the other, radical forms of social constructivism (whereby, in a caricature, with good bargaining skills even gravitation laws my be renegotiated with nature).

A somewhat complementary debate regards possible constraints (or lack of them) posed by specific technological paradigms upon the feasible forms of organization of production. For example an hypothesis on the emergence of the modern factory system of production is that it has been powerfully fostered by the associated efficiency improvement stemming from (i) the exploitation of inanimate source of energy; (ii) an increasing division of labor, and, together, (iii) more refined mechanisms of control upon the workforce and more favorable patterns of appropriation of the social products by the capitalist class. An alternatively hypotheses is, conversely, that only the latter set of factors was at work - the obvious normative implication being that an alternative organizational history could have been and could be easily imagined, subject to the collective will of social actors. For a revealing exchange on these questions, see Marglin (1974), Sabel and Zeitlin (1985), Landes (1986) and (1987).

Similar issues emerge with regard to the efficiency properties of "flexible specialization" as a possible general alternative to mass production (Piore and Sabel (1984), Sabel and Zeitlin (1995).

While it is impossible to enter the debate here, just notice that to a good extent the bottom line ha to do with degrees of plasticity of technological knowledge. Radical versions of both "economic inducement" and "social construction" theories imply highly malleable features of technologies: "money can buy everything" - in the former -, and "society can bargain everything" - in the latter.

Our view is much more cautious, and while fully acknowledging the profound reciprocal influences between technological, economic and social factors, maintain that the process of accumulation of technological knowledge entails an inner logic and inner constraints which social or economic drivers can hardly overcome at least in the short-term. A co-evolutionary perspective indeed implies a painstaking identification of the subtle intertwining between "windows of opportunity" for social action, on the one hand, and binding constraints inherited from history and/or from available technologies, on the other.

Techno-economic paradigms from micro technologies to national systems of innovation.

So far, we have discussed paradigms, trajectories or equivalent concepts mainly at micro-technological level. A paradigm-based theory of innovation and production - we have argued - seems to be highly consistent with the evidence on the patterned and cumulative nature of technical change and also with the evidence on micro economic heterogeneity and technological gaps. Moreover it directly links with those theories of production in economics which allow for dynamic increasing returns (from A. Young and Kaldor to recent and more rigorous formalized on path-dependent models of innovation diffusion), whereby the interaction between micro decisions and some forms of learning or some externalities produces irreversible technological paths and lock-in effects with respect to technologies which may well be inferior, on any measure, to other notional ones, but still happen to be dominant - loosely speaking - because of their weight of their history (Arthur 1989; David 1985; Dosi and Bassanini 2001).

The upside of the same story is that a world of knowledge-driven increasing returns is much less bleak that conventional economic theory has been preaching: there always are (partly) "free lunches", offered by ever-emerging opportunities for technological, organizational and institutional innovation. However, there is nothing automatic in the economic fulfillment of the notional promises offered by persistent and widespread learning process. Indeed the fulfillment of such promise ultimately depends upon matching/mismatching patterns between technological knowledge, the structure and behaviors of business organizations and broader institutional set-ups.

The steps leading from a microeconomic theory of innovation and production to more aggregate analyses are clearly numerous and complex. A first obvious question concern the possibility of identifying relatively coherent structure and dynamics also at broader levels of observation. Indeed, historians of technology - T. Hughes, B. Gilles and P. David, among others - highlight the importance of technological systems, that is in the terminology of this paper, structured combination of micro technological paradigms: see for example the fascinating reconstruction of the emerging system of electrification and electrical standards in David (1991), taken as an insightful guidance also for contemporary diffusion of ICT systems. One of the messages is that "retardation factors" in the economic realization of the promise are ubiquitous and they also recurrently explain what contemporaries in various epochs might have identified as an apparent "productivity paradox" - the puzzle emphasized by Robert Solow more than a decade ago - according to which computers show up everywhere but in statistics on productivity. As David points out also "in 1900 contemporaries might well have said that electric dynamos were to be seen 'everywhere but in the economic statistics'" (David 1991, p.315). The bottom line is that the lag is associated with the requirements of incremental improvements, organizational adaptation and ultimately "the path dependent nature of the process of transition between one techno-economic regime to the next" (David 1991, p.315).

At an even higher level of generality, Freeman and Perez (1988), Freeman and Louça (2001) and Perez (2002) have used the notion of techno-economic paradigms as a synthetic definition of macro-level system of production, innovation, political governance and social relations. So, for example, they identify broad phases of modern industrial development partly isomorphic to the notion of "regimes of socio-economic 'Regulation'" suggested by the manly French macro institutionalist literature (Aglietta 1976; Boyer 1988a, 1988b; see also Coriat and Dosi (1998a)).

In an extreme synthesis, both prospectives hold, first, that one can identify rather long periods of capitalist development distinguished according to their specific engines of technological dynamism and their modes of governance of the relationships amongst the major social actors (e.g. firms, workers, banks, collective political authorities, etc.) and, second, that the patterns of technological advancement and those of institutional changes are bound to be coupled in such ways as to yield recognizable invariances for quite long times in most economic and political structures. Just to provide an example, one might roughly identify, over the three decades after World War II, across most develops economies, some "Fordist/Keynesian" regime of socio-economic "Regulation", driven by major innovative opportunities of technological innovation in electromechanical technologies, synthetic chemistry, forms of institutional governance of industrial conflict, income distribution and aggregate demand management. Analogously, earlier in industrial history, one should be able to detect some sort of archetype of a "classical/Victorian Regime" driven in its growth by the full exploitation of textile manufacturing and light engineering mechanization, relatively competitive labor markets, politically driven effort to expand privileged market outlets, etc. (more on this in Coriat and Dosi (1998a).

These general conjectures on historical phases or regimes are grounded on the importance in growth and development of specific combinations among technological systems and forms of socio-economic governance. Figure 3, from Perez (2002) provides a suggestive taxonomy.

A complementary, somewhat more "cross-sectional", exercise concern the identification of national socio- economic regimes with distinctive embedding mechanisms of technological learning within national systems of innovation, production and governance.

So, even if micro paradigms present considerable invariances across countries, the ways they are combined in broader national systems of innovation display - we suggest - a considerable variety, shaped by county-specific institutions, policies and social factors. The hypothesis here is that evolutionary microfoundation are a fruitful starting point for a theory showing how technological gaps and national institutional diversities can jointly reproduce themselves over rather long spans of time in ways that are easily compatible with the patterns of incentives and opportunities facing individual agents, even when they might turn out to be profoundly suboptimal from a collective point of view.

At this level of analyses, inquires like those undertaken in different veins by Soskice (1997), Boyer and Hollingsworth (1997), Hall and Soskice (2001), Crouch and Streek (1997), Lazonick (2002), Dore (2000), starts where this chapter ends, addressing a few of the macro condition making up for diverse types of relatively coherent institutional combinatorics (e.g. underlying "Anglo-Saxon" vs. "Corporatist" system of innovation and production, etc.).

At this juncture, economic sociology, again, is bound to play a fundamental role, highlighting the social embedding of technological learning and its exploitation at work.

Table 1 - Major inventions, Discoveries and Innovations by Country (percentage of total)

Period	**Total**	**Britain**	**France**	**Germany**	**USA**	**Others**
1750-75	30	46.7	16.7	3.3	10.0	23.3
1776-1800	68	42,6	32.4	5.9	13.2	5.9
1801-25	95	44.2	22.1	10.5	12.6	10.5
1826-50	129	28.7	22.5	17.8	22.5	8.5
1851-75	163	17.8	20.9	23.9	25.2	12.3
1876-1900	204	14.2	17.2	19.1	37.7	11.8
1901-25	139	13.7	9.4	15.1	52.5	9.4
1926-50	113	11.5	0.9	12.4	61.9	13.3

Source: Dosi et al. (1990).

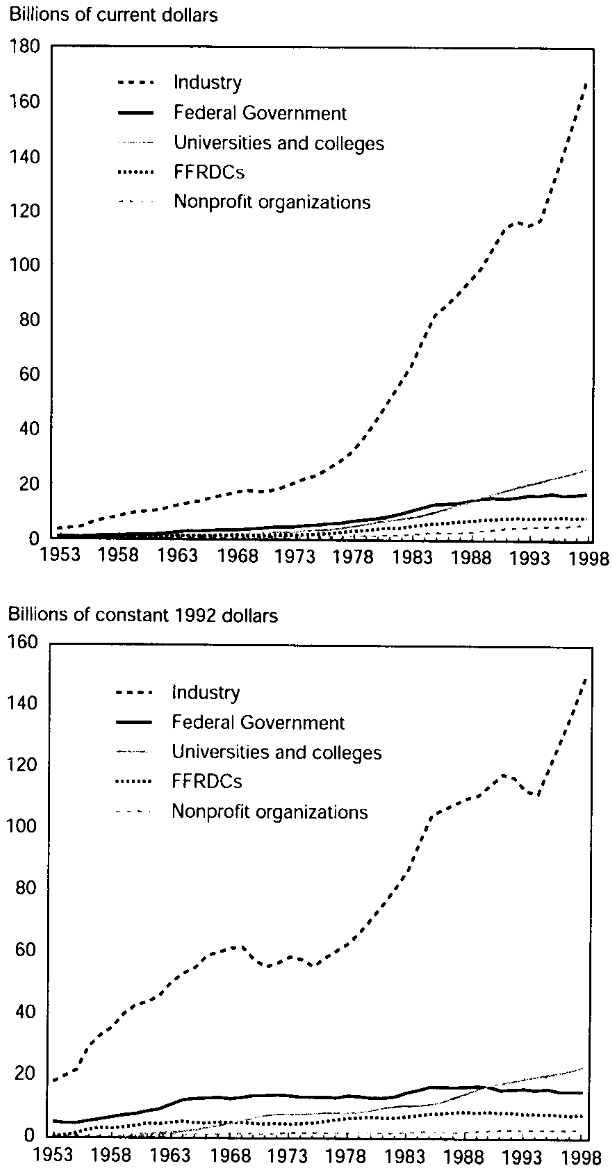
Table 2 - Patents Granted in the USA by Country of Origin, 1883-1986 (as a percentage of all foreign patenting).

	1883	**1900**	**1929**	**1958**	**1973**	**1986**	**1990**	**1995**	**1999**
Australia	1,11	2,33	1,96	0,6	0,92	1,14	1,01	1,00	1,02
Austria	2,62	3,36	2,47	1,12	1,02	1,09	0,91	0,74	0,69
Belgium	1,59	1,35	1,3	1,14	1,23	0,74	0,73	0,87	0,93
Canada	19,94	10,54	10,25	7,99	6,2	4,01	4,33	4,61	4,64
Denmark	0,56	0,46	0,71	0,74	0,7	0,56	0,37	0,44	0,70
France	14,22	9,79	9,76	10,36	9,38	7,22	6,67	6,18	5,49
Germany	18,67	30,72	32,36	25,6	24,25	20,8	17,72	14,45	13,42
Italy	0,24	0,92	1,19	3,02	3,39	3,05	2,93	2,36	2,14
Japan	0,16	0,03	1,4	1,93	22,1	40,35	45,43	47,64	44,70
Netherlands	0,24	0,75	1,57	5,71	3,03	2,2	2,23	1,75	1,79
Norway	0,32	0,49	0,71	0,61	0,42	0,25	0,26	0,28	0,32
Sweden	0,95	1,32	3,19	4,64	3,4	2,7	1,79	1,76	2,01
Switzerland	1,75	2,27	4,46	8,8	5,79	3,7	2,99	2,31	1,84
United Kingdom	34,55	30,52	22,23	23,45	12,56	7,37	6,49	5,42	5,13
Eastern Europe (including Russia)	0,40	1,49	1,62	0,55	2,53	1,13	0,35	0,26	0,29
NIC's	0,4	1,12	1,03	1,31	1,36	1,5	3,19	7,33	12,09
Others	3,28	2,54	3,07	2,43	1,72	2,19	2,61	2,59	2,79

Source: elaboration on Dosi et al. (1990) and National Science Board 2000.

Figure 1

Figure 1-2.
National R&D performance, by type of performer: 1953–1998



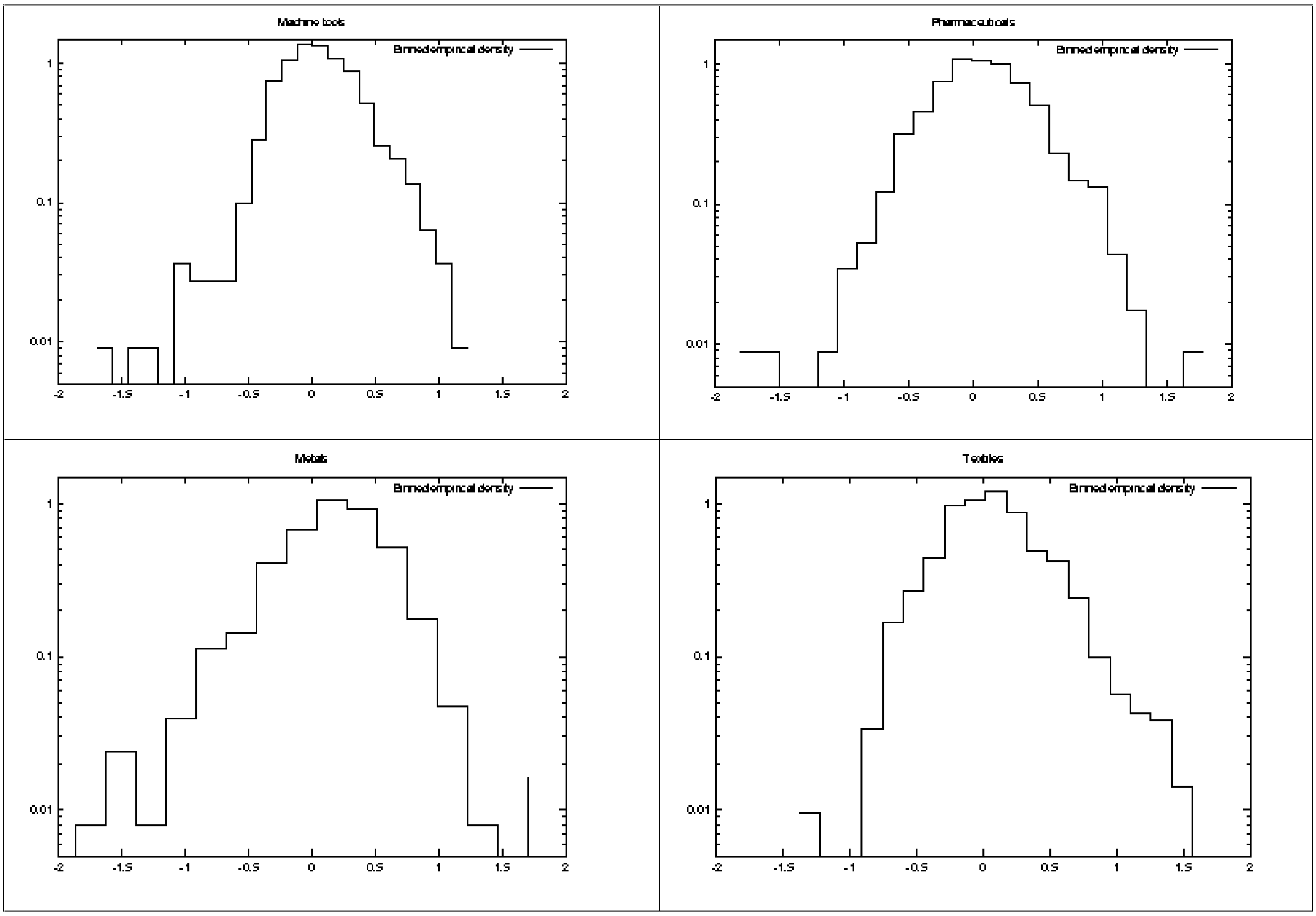
FFRDC = Federally Funded Research and Development Centers

See appendix tables 2-3 and 2-4.

Science & Engineering Indicators – 2000

Source: National Science Board 2000.

Figure 2 - Density Distribution of Labor Productivity (Normalized) in four Sectors of Italian Manufacturing: Machines tools, Pharmaceuticals, Metals, Textiles.



Source: Bottazzi, Cefis, Dosi and Secchi 2002

Table 3 - Moore’s Law: The trend in the number of transistors per chip over time

Microprocessor	Year	Transistors (8000S)	Clock Speed (MHz)
4004	1971	2.3	0.1
8008	1972	3.5	0.2
8080	1974	6.0	2.0
8086	1978	29.0	10.0
80286	1982	134.0	12.5
Intel 386	1985	275.0	16.0
Intel 486	1989	1200.0	25.0
Pentium	1993	3100.0	60.0
Pentium Pro	1995	5500.0	200.0
Pentium II	1997	7500.0	300.0
Pentium III	1999	9500.0	600.0

Source: National Science Board 2000

Figure 3

Figure 2.3. *A different techno-economic paradigm for each technological revolution: 1770 to 2000s*

TECHNOLOGICAL REVOLUTION Country of initial development	*TECHNO-ECONOMIC PARADIGM* 'Common sense' innovation principles
FIRST *The 'Industrial revolution'* Britain	Factory production Mechanization Productivity/ time keeping and time saving Fluidity of movement (as ideal for machines with water-power and for transport through canals and other waterways) Local networks
SECOND *Age of steam and railways* In Britain and spreading to Continent and USA	Economies of agglomeration/ Industrial cities/ National markets Power centers with national networks Scale as progress Standard parts/ machine-made machines Energy where needed (steam) Interdependent movement (of machines and of means of transport)
THIRD *Age of steel, electricity and heavy engineering* U.S.A . and Germany overtaking Britain	Giant structures (steel) Economies of scale of plant/ Vertical integration Distributed power for industry (electricity) Science as a productive force World-wide networks and empires (including cartels) Universal Standardization Cost accounting for control and efficiency Great scale for world market power/ 'Small' is successful, if local
FOURTH *Age of oil, the automobile and mass production* In USA and spreading to Europe	Mass production/Mass markets Economies of scale (product and market volume)/ Horizontal integration Standardization of products Energy intensity (oil based) Synthetic materials Functional specialization/ Hierarchical pyramids Centralization/ Metropolitan centers-suburbanization National powers, world agreements and confrontations
FIFTH *Age of information and telecommunications* In USA, spreading to Europe and Asia	Information- intensity (microelectronics based ICT) Decentralized integration/ Network structures Knowledge as capital / Intangible value added Heterogeneity, diversity, adaptability Segmentation of markets/ proliferation of niches Economies of scope and specialization combined with scale Globalization/ Interaction between the global and the local Inward and outward co-operation/ clusters Instant contact and action / instant global communications

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[1] Interpretations of technical change and a number of historical examples can be found in Freeman (1994),Rosenberg (1994), Nelson and Winter (1982), Hughes (1983), David (1975), Mokyr (1990), Saviotti (1996), Pavitt (1999), Dosi (1984), Basalla (1988), Constant (1980), Ziman (2000), among others; see for partial surveys Dosi (1988) and Freeman (1994).

[2] Incidentally note that the notion of dominant design is well in tune with the general idea technological paradigms but the latter do not necessarily imply the former. A revealing case to the point are pharmaceuticals technologies which do involve specific knowledge basis, specific search heuristics, etc. - i.e. the strong mark of paradigms - without however any hint at dominant design. Molecules, even when aimed at the same pathology, might have quite different structures: in that space, one is unlikely to find similarities akin those linking even a Volkswagen Beetle 1937 and a Ferrari 2000. Still, the notion of "paradigm" holds in terms of underlying features of knowledge bases and search processes.

[3] This is akin to the notion of reverse salient (Huges, 1983) and technological bottlenecks (Rosenberg, 1976): to illustrate, think of increasing the speed of a machine tool, which in turn demands changes in cutting materials, which leads to changes in other parts of the machine?

[4] See Pavitt (1991), Rosenberg (1990).

[5] In the literature, which admittedly includes some of the authors of this work, the two terms have been used quite liberally and interchangeably. In the introduction to Dosi, Nelson and Winter and more explicitly in Dosi, Coriat and Pavitt (2000) one proposes that the notion of capability ought to confined to relatively purposeful, "high level" tasks such as e.g. "building an automobile" with certain characteristics, while "competences", for sake of clarity might be confined to the ability to master specific knowledge bases (e.g. "mechanical" or "organic chemistry" competences). Clearly, such notion of competences/capabilities largely overlap with what has come to be known as the "competence view of the firm" (Prahalad and Hamel, 1990). Dosi, Nelson and Winter (2000) attempt to offer also some refinements within a rather germane perspective.

[6] These four sets correspond quite closely to the codified aspects of Lundvall's taxonomy, distinguishing know-what, know-why. know-who and know-how (Lundvall, 1995).

[7] This is also the title of an important research, in -progress, coordinated by Richard Nelson; for preliminary results, see Nelson (2001) and Nelson and Nelson (2002).

[8] The debate among historians about the role of science - or, to put it differently - of a positive attitude towards the rational manipulation of the environment and the rational adaptation of means to ends - for the emergence of the Industrial Revolution the is highly relevant in this context. See Landes (1968), Needham, (1954); Musson and Robinson (1969), among others. Of course, a general underlying issue regards "what is science" as distinguished from "what is technology". It is an issue that we cannot handle here. For our purposes suffice to recall the traditional and noble view shared by epistemologists as divers as Kuhn and Popper, pointing at the distinctions of science in terms of the procedures of discovery, validation and falsification and to somewhat overlapping distinction put forward by students of technology such as Vincenti (1990) based on different purposes of science, aiming at the understanding of "how things are" as opposed to the engineers focus on "how things ought to be". The distinction mirrors Lundvall's one between know-why and know-how. Notice that the foregoing views have been criticized by proponents of the "new economics of science" (see David and Dasgupta (1994) suggesting that science and technology primarily differ in terms of the ethos of the two communities concerning rules of disclosure of results, rules of attribution, etc.

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[9] A classic example may be found in the aircraft industry. The introduction of the turbojet spurred major advances in aerodynamics, aerothermodynamics and subsequently magnetothermodynamics, as further technological advances (e.g. higher speed) required a better understanding of underlying properties (Rosenberg, 1982; Constant, 1980).

[10] The expression is due to Freeman (1982).

[11] In this respect, it is quite interesting for example to read the documents written by academics and/or government officers to support funding for the emerging field of molecular biology in the 1950s-60s. Most of them do actually mention the potential benefits that scientific research in this area might have borne in the long run in terms of medical applications. However, in practice those considerations played a very minor role in the decision-making processes on how much and how actually funding molecular biology in the various European countries (See Krige (2000), Strasser (2000).

[12] For detailed discussions see Mowery (1981), Rosenberg (1982), Mowery and Rosenberg (1998), Nelson (1993), Freeman and Soete (1997), Pavitt (2000), Chandler (1977) and (1990), Hounsell (1996).

[13] More on all these points in Freeman and Soete (1997), Freeman (1994), Dosi (1988), Pavitt (2000).

[14] The classical example is biotechnology, where inventors - e.g. typically new specialized biotechnology firms (NBFs) - do not control the resources needed to develop the product, to go through the clinical trials and all the procedures needed to have the drug approved by regulatory agencies like the FDA and to market them. Under these circumstances, NBFs are in practice forced to license their invention to big pharmaceutical companies, thereby foregoing a large share of the profits generated by the sales of the drug (Teece, 1986).

[15] It is not possible to discuss here the underlying theoretical debates, ranging from "patent races models" to more reasonable "markets for technologies" analyses, all the way to evolutionary models of appropriability. Among many others see Stomeman (1995); Arora, Fosfuri and Gambardella (2001); Winter (1987).