Eurasian Business Review, 3(1), 2013, 3-46

THE EVOLUTION OF TECHNOLOGIES: AN ASSESSMENT OF THE STATE-OF-THE-ART

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Abstract: Scholars from a wide variety of disciplines who have studied technological advance in some detail have converged on the proposition that technological advance needs to be understood as proceeding through an evolutionary process characterized by multiple search efforts, deep inter-technological differences in the ways potential opportunities are tagged, ubiquitous uncertainty and innovation-driven competition among firms. In this work we survey the state-of-the-art in the analysis of such evolutionary processes. We start by asking whether there are some invariances in the knowledge structure and in the ways technological knowledge accumulates and, together, what distinguishes different fields and different periods of technological advance, if any. Next we address (i) the differences across paradigms in terms of nature and sources of innovative opportunities; (ii) the mechanisms of appropriation of economic returns from innovative activities; (iii) the role of demand and other socio-economic factors in shaping the directions of technological advances; (iv) the possibility of identifying discrete families sectors, distinct according to their sources of innovative knowledge and modes of innovating; (v) the relationships between the nature of productive knowledge and the distribution of input coefficients across firms; (vi) the patterns of innovation diffusion; and, finally, (vii) we discuss the role of history in the evolution of technologies, that is their path-dependence.

Keywords: Innovation, Evolution, Technological Paradigms, Trajectories, Appropriability, Opportunity, Innovation Diffusion, Technological Taxonomies, Path-Dependence

1. Introduction

Scholars from a wide variety of disciplines who have studied technological advance in some detail have converged on the proposition that technological advance needs to be understood as proceeding through an evolutionary process. Among economists and economic historians, the list includes Freeman (1982; 1994), Freeman and Soete (1997), Nelson (1981), Nelson and Winter (1977; 1982), Pavitt (1987; 1999), Rosenberg (1976; 1982), Winter (1982; 1987; 2005; 1968), Dosi (1982; 1988), Chandler (1992), Chandler and Galambos (1970), Mokyr (1990; 2002), Metcalfe (1994; 1998; 2005), Vincenti (1990), Ziman (2000), Dosi and Nelson (2010), on which this work largely draws.[1]

In a broad sense, the process is evolutionary meaning at least that at any time there generally are a wide variety of efforts going on to advance

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[1] Quite a few others, without explicitly calling themselves 'evolutionary' have expressed largely overlapping views, in primis Landes (1969; 1998) and David (1985; 1989; 2005), among quite a few others.

the technology, which to some extent are in competition with each other, as well as with the prevailing practices. The winners and losers in this competition are determined to a good extent through some *ex-post* selection mechanisms. At no instance the interpretation of the process gains much by trying to rationalize either in terms of consistent ‘gambles’ by forward looking players or by efficient ‘market processing’ over ex-ante blind ones. As such, the processes through which technologies evolve are also different in important respects from evolutionary processes in biology. In particular, the proposition that technology evolves in the above sense in no way denies, or plays down, the role of human purpose in the process, or the sometimes extremely powerful body of understanding and technique used to guide the efforts of those who seek to advance technology. Thus efforts at invention and innovation are by no means totally blind, or strictly random, as often is assumed to be the case regarding biological ‘mutation.’ At the same time, as we shall discuss below, purposefulness of search does not mean at all any accurate matching between forecasts and realized outcomes. Hence also the fundamental role of trials, errors and ex-post selection among competing variants of artifacts and processes of production.

Whenever efforts at inventing and designing are oriented in most cases by relatively strong professional understanding, *part* of the relevant variation, and the selection, which is involved in the evolution of technologies occurs in the human mind, in thinking and analysis, in discussion and argument, in exploration and testing of models, as contrasted with being out there in practice. Much of the effort to advance technology proceeds ‘off-line’, as it were. Research and development is the term customarily given to such off-line efforts, particularly when they involve groups of scientists and engineers working within a formal organization who have such work as their principal activity. Technologies and industries vary in regards to the amount of funds invested in R&D, and the extent to which R&D is the principal source of technological advance, as contrasted with learning by doing and by using. (The inter-sectoral evidence discussed in Dosi, 1988 and Pavitt, 1984; broadly applies also nowadays; see also below). However, even in fields where the science base is strong and the lion’s share of efforts to advance a technology proceed off line, learning-by-doing and by-using still plays an important role (cf. Rosenberg, 1982, ch.6 and Freeman, 1994). However, a general property holds throughout past and contemporary technologies: well codified ex ante knowledge, no matter how important, does not suffice to establish the detailed properties of any production process or artifact. There are three reasons. First, even where the underlying sciences are strong, a good part of the know-how that professionals bring to bear in their efforts to advance a technology is acquired through operating experience, rather than through formal training in the sciences. Second, in any case, efforts at inventing and solving technological problems inevitably reach beyond the range of options that are perfectly understood. Ultimately what works and what does not, and what works better than what, must be learned through actual experience.

Third, as we will highlight later, firms in an industry tend to differ from one another in the details of the products and processes they produce and employ, in the set of customers and suppliers they know well, and in their past history of successes and failures, all of which influences how they focus and undertake search activities. Such differences in knowledge and practice hardly come from either science or engineering principles, but rather form idiosyncratic experience.

Given these broad features of the process of innovation, let us ask whether there are some *invariances in the knowledge structure and in the ways technological knowledge accumulates* and, together, *what distinguishes different fields and different periods of technological advance, if any*. This is what we shall do in section 2. Next we shall address the differences across paradigms in terms of nature and sources of innovative opportunities (section 3) and mechanisms of appropriation of economic returns from innovative activities (section 4). In section 5 we address the role of demand and other socio-economic factors in shaping the directions of technological advances .Section 6 discusses the possibility of identifying discrete families sectors, distinct according to their sources of innovative knowledge and modes of innovating. Section 7 focuses on the relationships between the nature of productive knowledge and the distribution of input coefficients across firms. Section 8 briefly considers the patterns of innovation diffusion. Finally, in section 9, we discuss the role of history in the evolution of technologies, that is their path-dependence.

2. Technological Paradigms and Technological Trajectories

As we discuss at much greater length in Dosi and Nelson (2010), each technology needs to be understood as comprising (a) a specific body of practice - in the form of processes for achieving particular ends – together of course with an ensemble of required artifacts on the 'input side'; (b) quite often some distinct notion of a design of a desired 'output' artifacts; and, (c) a specific body of understanding, some relatively private, but much of it shared among professionals in a field. These elements, together, can be usefully considered as constituent parts of a *technological paradigm* (Dosi, 1982; 1988), somewhat in analogy with Thomas Kuhn's scientific paradigm (Kuhn, 1962).[2]

A paradigm embodies an *outlook*, a definition of the relevant problems to be addressed and the patterns of enquiry in order to address them. It entails a view of the purported needs of the users and the attributes

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[2] Here as well as in Dosi (1982), we use the notion of paradigm in a *microtechnological* sense: e.g. the semiconductor paradigm, the internal combustion engine paradigm, etc. this is distinct from the more 'macro' notion of 'techno-economic paradigm' used by Perez (1985; 2010), and Freeman and Perez (1988) which is a constellation of paradigms in our *narrow* sense: e.g. the electricity techno-economic paradigm, ICTs, etc. The latter broader notion overlaps with the idea of 'general purpose technologies' from Bresnahan and Trajtenberg (1995). (See also the remarks below, section 5). Moreover, the notion of paradigm used here bears a good deal of overlapping with that of 'regimes' put forward in Nelson and Winter (1977).

of the products or services they value. It encompasses the scientific and technical principles relevant to meeting those tasks, and the specific technologies employed. A paradigm entails *specific patterns of solution to selected techno-economic problems* – i.e. specific families of recipes and routines– based on highly selected principles derived from natural sciences, jointly with specific rules aimed at acquiring related new knowledge. Together, the paradigm includes a (generally imperfect) understanding about just how and (to some extent) why prevailing practice works.

An important part of paradigmatic knowledge takes the form of *design concepts* which characterize in general the configuration of the particular artifacts or processes that are operative at any time. Shared general design concepts are an important reason why there often is strong similarity among the range of particular products manufactured at any time - as the large passenger aircraft produced by different aircraft companies, the different television sets available at the electronics stores, etc. Indeed, the establishment of a given technological paradigm is quite often linked with the emergence of some *dominant design* (Abernathy and Utterback, 1978; Rosenbloom and Cusumano, 1987; Utterback and Suarez, 1993; Suarez and Utterback, 1995; Henderson and Clark, 1990; and the critical review of the whole literature in Murmann and Frenken, 2006). A dominant design is defined in the space of artifacts and is characterized both by a set of core design concepts embodied in components that correspond to the major functions performed by the product and by a product architecture that defines the ways in which these components are integrated (Murmann and Frenken, 2006; drawing upon Henderson and Clark, 1990). However, sometimes the establishment of a dominant paradigm is *not* associated with a dominant design. A revealing case to the point is pharmaceutical technologies which *do* involve specific knowledge basis, specific search heuristics, etc. - i.e. the strong mark of paradigms - without however any hint at any 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] Whether the establishment of a dominant paradigm entails also the established of a dominant design or not bears a lot of importance in terms of dynamics of industry structure along the life cycle of the industries to which a particular paradigm is associated.

Technological paradigms identify the operative constraints on prevailing best practice, and the *problem solving heuristics* deemed promising for pushing back those constraints. More generally, they are the cognitive frames shared by technological professionals in a field, that orient

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[3] A notion quite akin to ‘dominant design’ is that of ‘technological guideposts’ (Sahal 1981; 1985), a guidepost being the basic artifact whose techno-economic characteristics are progressively improved over time.

what they think they can do to advance a technology (Constant, 1980). Technological paradigms also encompass normative aspects, like criteria for assessing performance, and thus provide ways of judging what is better than what, and goals for the improvement of practice. Each paradigm involves a specific 'technology of technical change', that is specific *heuristics of search*. So, for example in some sectors, such as organic chemicals these heuristics relate to the ability of coupling basic scientific knowledge with the development of molecules that present the required characteristics, while in pharmaceutical the additional requirement is the ability to match the molecular knowledge with receptors and pathologies. In microelectronics search concerns methods for further miniaturization of electrical circuits, the development of the appropriate hardware capable of 'writing' semiconductor chips at such a required level of miniaturization and advances in the programming logic to be built into the chip. The examples are very many: a few ones are discussed in Dosi (1988). Here notice in particular that distinct (paradigm-specific) search and learning procedures, first, imply as such diverse modes of creating and accessing novel technological opportunities, and, second, entail also different organizational forms suited to such research procedures.[4] Both properties will turn out to be central when trying to characterize distinct 'regimes' of technological evolution (see below).

Together, the foregoing features of technological paradigms both provide a focus for efforts to advance a technology and channel them along distinct *technological trajectories*, with advances (made by many different agents) proceeding over significant periods of time in certain relatively invariant directions, in the space of techno-economic characteristics of artifacts and production processes. As paradigms embody the identification of the needs and technical requirements of the users, trajectories may by understood in terms of the progressive refinement and improvement in the supply responses to such potential demand requirements.

A growing number of examples of technological trajectories include aircrafts, helicopters, various kinds of agricultural equipment, automobiles, semiconductors and a few other technologies (Gordon and Munson, 1981; Sahal, 1981 and 1985; Dosi, 1984; Grupp, 1992; Saviotti and Trickett, 1992; Saviotti, 1996). So, for example, technological advances in aircraft technologies have followed two quite distinct trajectories (one civilian and one military) characterized by log-linear improvements in the tradeoffs between horsepower, gross takeoff weight, cruise speed, wing load and cruise range (Sahal, 1985; Frenken *et al.* 1999; Frenken and Leydesdorf, 2000; Giuri *et al.* 2007; and more specifically on aircraft engines Bonaccorsi *et al.* 2005). Analogously, in microelectronics, technical advances are accurately represented by an exponential trajectory of improvement in the

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[4] Note also that, there seems to be major differences between science-driven and technology-driven search (cf. Nightingale, 1998), with heuristics that in one case focus on 'puzzles further ahead' – given what one knows – while in the technological domain, heuristics typically address 'how can one solve this problem', irrespectively of the underlying theoretical knowledge.

relationship between density of electronic chips, speed of computation and cost per bit of information (see Dosi, 1984, but the trajectory has persisted since then). As an illustration consider Figure 1, from Nordhaus (2007) highlighting also the changing trajectories associated with paradigm changes, and Figure 2 pointing out the long-term trajectory-like pattern and the ways it has been punctuated by different families of devices. In fact, it is fair to say that trajectory-like patterns of technological advance have been generally found so far whenever the analyst bothered to plot over time the fundamental techno-economic features of discrete artifacts or processes, say from the DC3 to the Airbus 380, among aircrafts, or from crucible to Bessemer to basic oxygen reduction among steel making processes. (Admittedly, trajectories in the space of processes and related input intensities have been studied much less than trajectories in the output characteristic space, and this is indeed a challenging research area ahead).

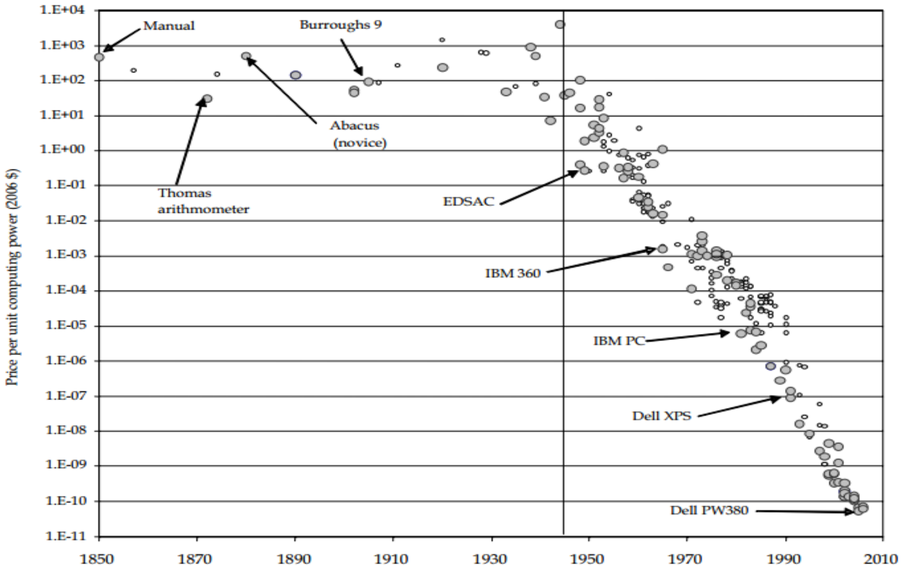

Figure 1. The progress of computing measured in cost per computation per second deflated by the price index for GDP in 2006 prices

Source: Nordhaus (2007)

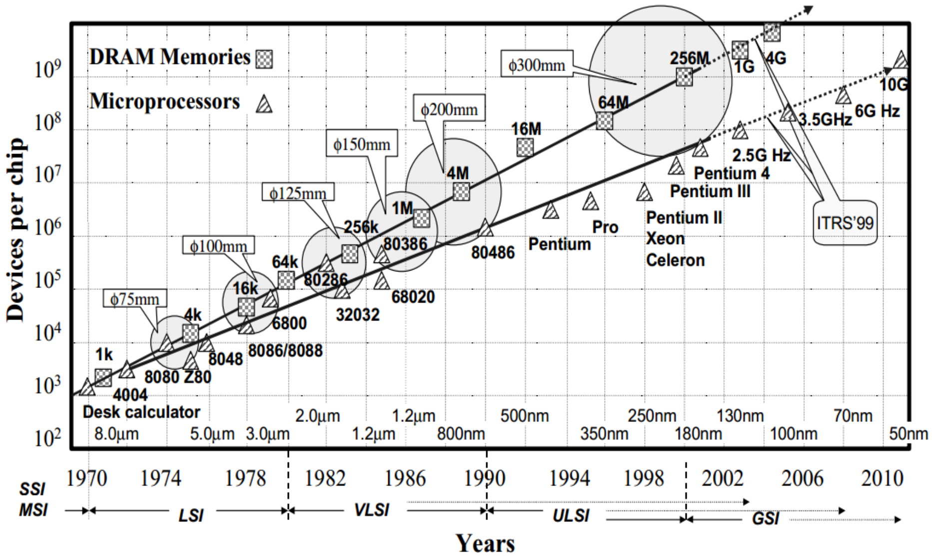

Figure 2. Moore's law and technology scaling

Source: Zheng (2008)

The emergence of relatively ordered trajectories, as already hinted, sometimes is and sometimes is not associated with the emergence of dominant designs. When it does, the trajectories appear to be driven by 'hierarchically nested technological cycles' entailing both relatively invariant core components improving over time and a series of bottlenecks and 'technological imbalances' (Rosenberg, 1976) regarding the consistency among all the components of the systems (cf. Murmann and Frenken, 2006). Come as it may, some properties of trajectories are important to notice here.

First, trajectories *order* and *confine* but do not at all eliminate the persistent *generation* of *variety*, in the product- and process-spaces, which innovative search always produces. The paradigm defines proximate boundaries of feasibility and together shapes the heuristics of search. However there continues to be plenty of possible trade-offs between output characteristics which different producers explore (Saviotti, 1996) and which will be eventually the object of (imperfect and time-consuming) market selection.

Second, by the same token, trajectories so to speak 'extrapolated forward' - in so far as their knowledge is shared by the community of firms, practitioners, engineers – are a powerful *uncertainty reducing representations* of what the future is likely to yield in technological terms. However, this remains a far cry from any unbiased expectation on the time and costs involved in 'getting there'- wherever 'there' means – and, even more so, of the probability distributions of individual actors over both technological and economic success. That is trajectories are not means to reduce Knightian uncertainty into probabilizable risk.[5] Indeed, notwithstanding roughly predictable trajectories of advance, both *substantive uncertainty* – concerning future states-of-the-world – and *procedural uncertainty* – regarding yet to come problem-solving procedures – continue to be ubiquitous.[6]

Note that there is no a priori economic reason why one should observe limited clusters of technological characteristics at any one time and ordered trajectories over time. On the contrary, as we already argued in Dosi (1988) - given consumers with different preferences and equipment users with different technical requirements, and different relative prices over different countries, if technologies were perfectly ‘plastic’ and malleable – as standard economic representations are implicitly suggesting – one would tend to observe sorts of ‘isoquants’ in the space of techniques and techno-economic characteristics and products with the familiar shape. And, over time, if technological recipes – both in the procedural aspects and their input contents – could be freely added, divided, recombined, substituted, etc. one would also tend to observe an increasingly disperse variety of technical and performance combinations in products, production inputs and available techniques (even if not necessarily in their use, given relative prices). The ubiquitous evidence on trajectories, on the contrary, suggests that technological advances are circumscribed within a quite limited subset of the techno-economic characteristics space. We could say that the paradigmatic, cumulative, nature of technological knowledge provides *innovation avenues* (Sahal, 1985) which channel technological evolution, while major discontinuities tend to be associated with changes in paradigms. Indeed, here and throughout we shall call ‘normal’ technical progress those advances occurring along a given trajectory - irrespectively of how ‘big’ they are and how fast they occur- while we reserve the name of ‘radical innovations’ to those innovations linked with paradigm changes.

A change in the paradigm generally implies a change in the trajectories. Together with different knowledge bases and different prototypes of artifacts, the techno-economic dimensions of innovation also vary. Some characteristics may become easier to achieve, new desirable characteristics may emerge, some others may lose importance. Relatedly, the engineers’ vision of future technological advances changes, together with a changing emphasis on the various tradeoffs that characterize the new artifacts. So, for example, the technological trajectory in active electrical components based on thermionic valves had as fundamental dimensions heat-loss vacuum-parameters, miniaturization and reliability over time. With the appearance of solid state components (the fundamental

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[5] Such persistent uncertainty is also reflected by systematic forecasting errors concerning costs of innovative search, future demand and future profitabilities of new products and processes: see Starbuck and Mezias (1996) Beardsley and Mansfield (1978), Freeman and Soete (1997), Dawid (2006) and Gary *et al.* (2008), among others. Indeed all evidence points in a direction opposite to any assumption of ‘rational technological expectations’!

[6] More on the notions of substantive and procedural uncertainty in Dosi and Egidi (1991). For a discussion of the related modeling efforts, cf. Dawid (2006).

building block of the microelectronic revolution) heat loss became relatively less relevant, while miniaturization increased enormously in importance. Similar examples of change in the dimensions of the design space can be found in most transitions from one paradigm to another.

Are there some features which most technological trajectories share?

A common feature which characterizes trajectories in process technologies and in the related equipment-embodied technologies is a powerful trend toward mechanization and/or automation of production activities. Recent pieces of evidence are in Klevorick *et al.* (1995), but the phenomenon has been noticed since the classics and plays an important role in the analyses of the dynamics of capitalist economies by Adam Smith and Karl Marx. Note that such a tendency holds across sectors and across countries characterized by different capital intensities and broadly occurs irrespectively of variations in relative prices.[7] Due to its generality, in another work (Nelson and Winter, 1977) we called it a 'natural trajectory': of course there is nothing 'natural', strictly speaking, but it is indeed a general reflection of a long term trend toward the substitution of inanimate energy to human and animal efforts, and more recently also of inanimate information processing to human cognition and control.

There is another relatively common feature of trajectories of innovation (even if we still do not know how common – a task indeed for empirical research ahead), namely *learning curves* (much more on them in Thompson, 2010). Let us just mention some basic regularities and their bearing on the properties of technological trajectories. It has been found that costs fall according to a power law of the kind

$$p = \alpha * X^{\beta} \qquad (1)$$

where X is the cumulated production, α and β are two (technology-specific) constants, and p generally stands for unit costs but sometimes represents unit labor inputs or also some indicator of product performance. This original statement of the 'law' comes from Wright (1936)[8] based on aircraft manufacturing (see also Alchian, 1963). Similar regularities appear in various energy producing technologies, in computers, light bulbs, and many other artifacts and processes: for technology-specific evidence and surveys see Conley (1970), Baloff (1971) Dutton and Thomas (1984), Gritsevskyi and Nakicenovic (2000), MacDonald and Schrattenholzer (2001), Neij (1997), Yelle (1979), Argote and Epple (1990), and Thompson (2010). Semiconductors offer an archetypical example of a trajectory driven by miniaturization efforts yielding the so-called Moore's law involving the doubling of the density of elementary transistor-per-chip and later microprocessors every 2-3 years (cf. Figure 2; more details in Gordon and

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[7] For some more detailed discussion, cf. also Dosi *et al.* (1990).

[8] Who, somewhat confusingly, calls 'performance' the left hand variable and 'prevalence' the right hand one.

Munson, 1981; Dosi, 1984; Nordhaus, 2007; and Jovanovic and Rousseau, 2002).[9]

Interestingly, a steady fall in unit labor inputs seems – at least in some circumstances – to appear even when holding the equipment constant. It is the so-called ‘Horndahl effect’, named after a Swedish steel mill (Lundberg, 1961 cited in Arrow, 1962b), which contributed to inspire Arrow (1962b) on learning by doing.[10] Notice that learning effects appear at the levels of industry, firms and plants, even if distinct rates and intertemporal variabilities with micro learning displaying higher irregularities over time than industry-level rates of progress(for some discussion of the evidence see Auerswald *et al.* 2000). The interpretation of learning mechanisms underlying the observed performance trajectories of their differences across different paradigms are indeed important tasks ahead for evolutionary analyses of innovation.[11]

Together with differences across paradigms in the rates of technological advance, one observes major differences in the processes through which such advances occur. In fact, significant progress has been made in the conceptualization of what different technological paradigms have in common and how they differ in terms of the sources of knowledge upon which they draw – that is the *technological opportunities* which they tap -, the mechanisms through which such opportunities are seized, and the possibilities they entail for innovators to extract economic benefit from their technological advances – that is the *appropriability conditions*.

Let us consider these properties.

3. Technological Opportunities, the Processes of Knowledge Accumulation, and their Cumulativeness

Prevailing technological paradigms differ over time and across fields regarding the nature of the knowledge underlying the opportunities for technical advances. Relatedly, they differ in the extent to which such knowledge has been gained largely through operating experience, as contrasted to scientific research.

While in most fields there is a mix, in the fields generally thought of as ‘high tech’ a more significant contribution is nowadays grounded in specialized fields of science or engineering.

Where operating experience and learning by doing and using, are the primary basis for professional understanding, as was the case with

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[9] Moore’s Law, technically, is formulated in terms of time rather than cumulated output such as in equation (1). However, it can be easily reformulated accordingly, noticing that output flows exhibit an exponential growth profile over time.

[10] Strictly speaking, the Horndahl effect showed around 2% per year growth in productivity, and thus, again, related performance with time and experience rather than accumulated output, but see footnote 21.

[11] For more evidence on the characteristics of specific paradigms and trajectories see also Consoli (2005); Chataway *et al.* (2004); Mina *et al.* (2007); Possas *et al.* (1996); Dew (2006), Castaldi *et al.* (2009) among many others.

Mandeville's example of 18th century ship design, the learning trajectory is going to advance paced by experience with actual new designs (and nowadays with the advances incorporated into new vintages of capital equipment and ability of using it). In the other hand, understanding can advance rapidly when there are fields of science dedicated to that objective. Several recent studies (see e.g. Klevorick *et al.* 1995; Nelson and Wolff, 1997) have shown that the fields of technology that, by a variety of measures, have advanced most rapidly are associated with strong fields of applied science or engineering. Moreover, firms operating in these fields also tend to have higher than average levels of R&D intensity. In fact, in a secular perspective, the evidence is in tune with Mokyr's general conjecture that the 'epistemic' elements of technological knowledge – that is those elements associated with an explicitly casual knowledge of natural phenomena – have had a crucial (and increasing) importance in modern technological advances (Mokyr, 2002 and 2010; Nelson, 2003; Nelson and Wolf, 1997; and Nelson and Nelson, 2002).

Since the Industrial Revolution, the relative contribution of sciences to technology has been increasing, and in turn such a science base has been largely the product of publicly funded research, while the knowledge produced by that research has been largely open and available for potential innovation to use (more in David, 2001a, 2001b and 2004; Nelson, 2004; and Pavitt, 2001).

This, however, is not sufficient to corroborate any simple 'linear model' from pure to applied science, to technological applications.

First, the point made elsewhere by Rosenberg (1982) Kline and Rosenberg (1986), Pavitt (1999), Nelson (1981) continues to apply: scientific principles help a lot but are rarely enough. An enlightening case to the point, indeed in a 'science-based' area – medical innovation – is discussed in Rosenberg (2009). Semiconductors technology is another good example. For many decades, efforts to advance products and process technology – crucially involving the ability to progressively make circuits smaller and smaller – have taken advantage of the understandings in material science and the underlying solid state physics. However, much more pragmatic and tacit elements of technological knowhow have persistently been crucial.

Second, it is quite common that scientific advances have been made possible by technological ones, especially in the fields of instruments: think of the example of the electronic microscope with respect to the scientific advances in life sciences (more in Rosenberg, 1982; 1994).

Third, it is not unusual that technologies are made to work before one understands why they do: the practical (steam) engine was developed some years before science modeled the theoretical Carnot engine; even more strikingly, the airplane was empirically proved to work few decades before applied sciences 'proved' that it was theoretically possible![12] In fact, the specificities of the links between technological advances and advances in applied sciences are a major discriminating factor among different technological paradigms and different sectors (see below on sectoral taxonomies).

Generally speaking, while it usually holds that technological advance tends to proceed rapidly where scientific understanding is strong and slowly where it is weak, the key has often been the ability to design controllable and replicable practices that are broadly effective around what is understood scientifically. [13] (For a more detailed discussion, see Nelson, 2008).

Given whatever potential opportunities for innovation, what are the properties of the processes through which they are tapped? An important feature distinguishing different paradigms has to do with the *cumulativeness* of innovative successes. Intuitively, the property captures the degrees to which 'success breeds success', or, in another fashionable expression, the measure to which innovative advances are made by dwarfs standing on the shoulders of past giants (as such, possibly, the integral of many dwarfs). Cumulativeness captures the incremental nature of technological search, and, crucially, varies a lot across different innovative activities (Breschi *et al.* 2000; Malerba and Orsenigo, 1996; see also below). More formally, a way to capture cumulativeness is in terms of *future probabilities* of success conditional on *past realizations* of the stochastic process. In that respect, it is a widespread instance of *knowledge-based dynamic increasing returns*.

Quite a few technological paradigms embodying knowledge generated to a large extent endogenously tend to display dynamics of knowledge accumulation which are more cumulative than trajectories of advance which are, so to speak, fuelled 'from outside' (e.g. via the acquisition of new pieces of equipment generated in other industrial

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[12] In fact, history quite often offers examples of a co-evolutionary kind with the main arrow of causation running in one direction or the other depending also on the period and stage of development of knowledge. Take the case of the steam engine. While it is true that practical advances in the first half of the 18th century preceded subsequent advancement in classical thermodynamics and the theory of heat engines, it also hold that earlier attempt to exploit the power of steam were palpably influenced by the scientific investigations of Torricelli, Pascal, Boyle and Hooke on the existence and properties of atmospheric pressure (Kerker, 1961). This may also explain why the steam engine was not invented in China, even if all constituent parts (piston, cylinder, etc.) were available also there (Needham, 1962).

[13] Note that this property does not bear any direct implication in terms newness of the scientific understanding itself. Moreover, high rates of advance often occur when new pieces of knowledge (new paradigms) are applied to older, much less science-based technologies. ICT applications to industrial machinery used in 'traditional' industries are a good case to the point.

sectors). A further distinction concerns the *domain* at which cumulative learning tends to occur. It is at the level of individual firms or is it at the level of the overall community of firms, would-be entrepreneurs, technical communities associated with each paradigms, etc.? In Teece *et al.* (1994), one points at examples such as Intel where cumulativeness applies at both paradigm- and firm-level. At the opposite extreme, many instances point at patterns of technological change which are anti-cumulative in that they imply *competence-destruction* at the level of individual incumbents (cf. Tushman and Anderson, 1986). Yet other historical examples highlight discontinuities engendered by firms specific *organizational diseconomies of scope* even under largely cumulative industry-level patterns of accumulation of technological knowledge: Bresnahan *et al.* (2008) offer a vivid illustration concerning the introduction of the PC and the browser in the case of IBM and Microsoft, respectively.

4. Means of Appropriation

Most researchers at universities and public laboratories do their work, which on occasion may result in a significant technological advance, without expectation of benefiting directly from it financially. Some inventors invent because of the challenge of it, and the sense of fulfillment that comes with solving a difficult problem. And, more important, as already mentioned, in contemporary societies most scientific knowledge – of both the 'pure' and 'applied' nature – has been generated within a regime of *open science*. The fundamental vision underlying and supporting such a view of publicly supported open science throughout a good part of the 20th century entailed (i) a sociology of the scientists community largely relying on self-governance and peer evaluation, (ii) a shared culture of scientists emphasizing the importance of motivational factors other than economic ones and (iii) an ethos of disclosure of search results driven by 'winner takes all' precedence rules.[14] In Nelson (2006), David and Hall (2006) and Dosi *et al.* (2006) one discusses the dangers coming from the erosion of Open Science institutions. We cannot get into detail here. We have already mentioned above the importance of (free flowing) advances in pure and applied sciences as a fundamental fuel for technological advances – albeit with significant variation across technologies, sectors and stages of development of each technological paradigm. However, the major share of inventive activities finalized to economically exploitable technologies that goes on in contemporary capitalist societies is done in profit-seeking organizations with the hope and expectation of being economically rewarded, if that work is successful. In turn, the very existence of a relation between economically expensive search efforts by private agents, and (uncertain) economic rewards from successful innovations, entails the

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[14] On those points following the classic statements in Bush (1945), Polanyi (1962) and Merton (1973), see the more recent appraisals in Dasgupta and David (1994); David (2004); Nelson (2004) and the conflicting views presented in Geuna *et al.* (2003)

fundamental incompatibility – originally pointed out by Marx and Schumpeter – between any sort of zero-profit general equilibrium and any incentive to *endogenous* innovation (that is, endogenous to the private, 'capitalist', sector of the economy).

Granted that, however, two major sets of questions arise.

First, how profound is such a trade-off, if any, between monopolistic departures from competitive (zero profit) conditions and incentives to innovate? [15] More precisely, what is the evidence, if any, on some monotonic relation between (actual and expected) returns from innovation, on the one hand, and innovative efforts, on the other?

Such a monotonic relation is in fact built-in as one of a core assumption within most 'neo-Schumpeterian' models of growth, while the limited ability to appropriate returns to invention and innovation often is offered as the reason why the rate of technological progress is very slow in some industries. The afore mentioned studies on the nature and sources of technological opportunities suggest that this is unlikely to be the primary reason. Rather, it is far more likely that the reason for the highly uneven rates of progress among industries lies in differences in the strength and richness of technological opportunities. More generally let us suggest that the widespread view that the key to increasing technological progress is in strengthening appropriability conditions, mainly through making patents stronger and wider, is deeply misconceived. Obviously, inventors and innovators must have a reasonable expectation of being able to profit from their work, where it is technologically successful and happens to meet market demands. However, in most industries this already is the case. And there is no evidence that stronger patents will significantly increase the rate of technological progress. (More in Mazzoleni and Nelson, 1998; Jaffe, 2000; Granstrand, 1999; Dosi *et al.* 2006; and the growing literature cited therein). In fact, in many instances the opposite might may well be the case. We have noted that in most fields of technology, progress is cumulative, with yesterdays efforts, both the failures and the successes, setting the stage for today's efforts and achievements. If those who do R&D today are cut off from being to draw from and build on what was achieved yesterday, progress may be hindered significantly. Historical examples, such as those presented in 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 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

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[15] Note that the possible 'trade-off' discussed here is distinct from the purported, and somewhat elusive ('Schumpeterian') trade-off referred to in the literature between propensity to innovate and market structure: more on the theoretical side in Nelson and Winter (1982), and on the empirical evidence Cohen and Levin (1989) and Soete (1979), among others.

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 inventions.

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 not 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. In this respect, Murray *et al.* (2009) offer a striking illustration of how 'opening up upstream' (again, in the case of the mouse) – in such an instance, a discrete change in the IPR regime in the U.S. – yielded more search / more diverse rates of exploration of 'downstream' research paths.[16]

In general, today's efforts to advance a technology often need to draw from a number of earlier discoveries and advances which painstakingly build upon each other. Under these circumstances IPRs are more likely to be a hindrance than an incentive to innovate. (More in Merges and Nelson, 1994; and Heller and Eisenberg, 1998). If past and present components of technological systems are patented by different parties, there can be an *anti-commons* problem (the term was coined by Heller and Eisenberg). While in the standard commons problem (such as an open pasture) the lack of proprietary rights is argued to lead to over-utilization and depletion of common goods, in instances like biotechnology the risk may be that excessive fragmentation of IPRs among too many owners which may well slow down research activities because each owner can block each other. Further empirical evidence on the negative effects of strong patent protection on technological progress is in Mazzoleni and Nelson (1998); and at a more theoretical level, see the insightful discussion in Winter (1993) showing how tight appropriability regimes in evolutionary environments might deter technical progress (cf. also the formal explorations in Marengo *et al.* 2009). Conversely, well before the contemporary movement of 'open source' software, one is able to document cases in which groups of competing firms or private investors, possibly because of some awareness of the anti-commons problem, have preferred to avoid claiming patents and, on purpose, to operate in a weak IPR regime somewhat similar to that of open science, involving the free disclosure of inventions to one another: see Allen (1983) and Nuvolari

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[16] It is not possible to discuss here the underlying theoretical debates: let us just mention that they range from 'patent races' equilibrium models (cf. the discussion in Stoneman, 1995) to much more empirically insightful 'markets for technologies' analyses (Arora *et al.* 2002), all the way to evolutionary models of appropriability (Winter, 1993).

(2004) on blast furnaces and the Cornish pumping engine, respectively. Interestingly these cases of ‘collective invention’ have been able to yield rapid rates of technical change. Similar phenomena of free revelation of innovation appear also in the communities of users innovators: see von Hippel (2005).

The *second* set of questions regards the characteristics of the regimes stimulating and guiding technological advance in a field of activity, that is *how* inventors appropriate returns. The conventional wisdom long has been that patent protection is the key to being able to appropriate them. But this is the case only in some fields of technology. Pharmaceuticals is an important example. However, a series of studies (Mansfield *et al.* 1981; Levin *et al.* 1985; Cohen *et al.* 2002; among others) has shown that in many industries patents are not the most important mechanism enabling inventors to appropriate returns. Thus Levin *et al.* (1985, p.33), find that for most industries

> ‘lead time and learning curve advantages, combined with complementary marketing efforts, appear to be the principal mechanisms of appropriating returns to product innovations’.

Patenting often appears to be a complementary mechanism for appropriating returns to product innovation, but not the principal one on most industries. For process innovations (used by the innovator itself) secrecy often is important, patents seldom so. These findings were largely confirmed by a follow-on study done a decade later by Cohen *et al.* (2002). David Teece (1986) and a rich subsequent literature (cf. the Special Issue of *Research Policy*, 35(8), 2006; taking stock on the advancements since his original insights) have analyzed in some detail the differences between inventions for which strong patents can be obtained and enforced, and inventions where patents cannot be obtained or are weak, in the firm strategies needed for reaping returns to innovation. A basic and rather general finding is that in many cases building the organizational capabilities to implement and complement new technology enables returns to R&D to be high, even when patents are weak. Thus, despite the fact that patents were effective in only a small share of the industries considered in the study by Levin *et al.* (1985), some three-quarters of the industries surveyed reported the existence of at least one effective means of protecting process innovation, and more than ninety percent of’ the industries reported the same regarding product innovations (Levin *et al.* 1985). 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 cf. Arundel *et al.* (1995).

If there are some bottom lines so far to this broad area of investigation, they are that, *first*, there is no evidence on any monotonic relation between degrees of appropriability and propensity to undertake innovative search, above some (minimal) appropriability threshold; *second*, appropriability mechanisms currently in place are well sufficient (in fact, possibly overabundant); *third* the different rates of innovation across sectors and technological paradigms can be hardly explained by variations in the effectiveness of appropriability mechanisms, and, *fourth*¸ even less so by differences in the effectiveness if IPR protection.

5. Demand and Other Socio-economic Factors Shaping the Direction of Technological Advance

The tendency of the advance of a technology to follow a particular trajectory is not an indication that user needs and preferences and economic conditions such as relative prices do not affect the path of technological development. While the nature of technological opportunities does limit the range of directions along which a technology can advance, there generally is still significant scope for variation, and, as mentioned above, built into the paradigms that guide technological development are also a set of understandings about users' would-be requirements.

Let us consider in more detail the interplay between knowledge driven venues of search and mechanisms of economic inducement.

A widespread view is that, in fields where the underlying science is strong, efforts to advance the technology generally are triggered by new scientific knowledge, and are directed to taking advantage of that new knowledge. While there certainly are quite a few circumstances where new science has directly stimulated new inventive efforts, several studies suggest that usually this is not the case, with the science being applied in industrial R&D usually not being particularly new. Conversely, these same studies show that efforts to advance practice are very strongly influenced by perceptions of what users value or at least by the perception of a problem with clear practical applications: see the evidence collected in Project Sappho and reported in Freeman (1982), similar findings on the importance of perceived user needs are reported in Cohen *et al.* (2002). At the same time, considerations of technological feasibility tend to influence how these perceived demands are addressed. Thus an important aspect of the technological regime that shapes progress in a field is the character of the user community, their wants and constraints, more generally the (perceived) market for the new products and services that efforts to advance the technology might engender.

User markets differ greatly both in the nature of the needs and preferences they reflect, and in the sophistication of the purchasers. Thus to sell their wares to the airlines, the producers of large passenger aircraft know their designs have to meet a long list of quite precise requirements, that the airlines have the technical sophistication to assess quite accurately. There also are regulatory safety standards that a new aircraft must pass before airlines can purchase and use it. Hence, the market for large commercial aircraft is far more tuned to technical characteristics of the product, far less moveable by advertising aimed to influence tastes, than say the market for automobiles. The market for operating system software mostly consists of the designers and producers of computers for whom various technical qualities are important, while the market for software games is mainly individuals who are attracted by different sorts of product quality. Indeed, there have been several studies that have explored the reasons why certain technological innovations were successful commercially while other ones, similar in many technical respects, were not. The principal factor often turned out to be understanding of the needs and desires of users by the successful innovator (see the still classic Sappho project, comparing innovative successes and failures across otherwise similar firms: cf. Freeman, 1982).

Granted such broad and widespread interactions between users' demands and technological advances, it holds also that each body of knowledge specific to particular technologies, i.e. each paradigm shapes and constrains the notional opportunities of future technical advance and also the boundaries of the set of input coefficients which are feasible on the grounds of that knowledge base (so that, for example, irrespectively of the relative price of energy, it is difficult to imagine, giver our current knowledge base, a technology for the production of hyperpure silicon which would not be very energy-intensive …).

Within such boundaries, change in the orientation of the new technologies created and developed can be induced by changes in demand-side factors in four analytically different ways.[17]

First, within a particular paradigm changes in relative prices and demand or supply conditions may well affect the orientation of search heuristics. This is what Rosenberg (1976) has called *focusing devices*, and historically documented in a few cases of supply shocks and technological bottlenecks (see also the notion of 'reverse salients' by Hughes, 1983), from the continental blockade during Napoleonic wars to the history of various technical bottlenecks in mechanical technologies. The mid 19th century history of machine tools provides indeed a fascinating example. Users always wanted tools that would cut faster, and inventors and designers responded. As higher cutting speeds were achieved, this put stress on the metals used in the machine blades. New blade materials were invented. And higher speeds also increased the temperatures at which blades had to operate; better cooling methods were invented and developed. (Bounded rationality and lack of 'rational' technological expectations stand behind the relevance of these behaviorally-mediated inducements effects. But, as already mentioned, evolutionary theories – quite in tune with empirical evidence – are at ease with these assumptions.)

Other powerful and quite general environment inducement factors have to do with industrial relations and industrial conflict. As analyzed by Rosenberg (1976), the resistance of 19th century English labor, especially skilled labor, to factory discipline and terms of employment, has acted as a powerful stimulus to technical change. As Karl Marx vividly put it

> 'In England, strikes have regularly given rise to the invention and application of new machines. Machines were, it may be said, the weapon employed by the capitalists to equal the result of

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[17] For important discussions of 'inducement effects', cf. Binswanger and Ruttan (1978), and Ruttan (1997).

> specialized labor. The self-acting mule, the greatest invention of modern industry put out of action the spinners who were in revolt. If combinations and strikes had no other effect than of making the efforts of mechanical genius react against them , they would still exercise an immense influence on the development of the industry' (Marx, 1847, p.161; also cited in Rosenberg, 1976).

Similarly, industrial conflict has been a powerful driver of the trajectories of mechanization of production based on taylorist principles (Coriat and Dosi, 1998).

Symmetrically, on the demand side, along with obvious feasibility conditions, users' requirements have a major influence on the ensuing trajectories in the products characteristic space. As illustrations, think of the role of the requirements of the space and military industry on the early (U.S. and world) trajectories in semiconductor devices, or the influence of the characteristics of the U.S. market on the trajectories of product innovation in automobile (in this case, largely specific to North America). And of course the extreme case of users requirements influencing the patterns of innovation is when users themselves are innovators (von Hippel, 2005).

In all these instances, 'inducement' stands for the influences that the actual or perceived environmental conditions exert upon the problem-solving activities which agents decide to undertake.

The earlier caveat that knowledge bases constrain the directions of search is crucial as well, and this applies to both single technologies and broad technological systems (or 'techno-economic paradigms' in the sense of Perez, 1985; and Freeman and Perez, 1988) which dominate in the economy over particular phases of development (e.g. steam power, electricity and electromechanical technologies, microelectronics and information technologies, etc.). Consider for example, Moses Abramovitz's proposition that

> 'in the nineteenth century, technological progress was heavily biased in a physical capital-using direction [and] it could be incorporated into production only by agency of a large expansion in physical capital per worker … [while] … in the twentieth century … the bias weakened [and] may have disappeared altogether' (Abramovitz, 1993, p.224).

As we read it, it is a proposition on the nature of the knowledge available at a certain time in the society and the ways it constrains its economic exploitation, irrespectively of relative prices. That is, the proposition concerns the boundaries of the opportunity set attainable on the grounds of the available paradigms[18] and the limits to possible 'inducement effects'.

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[18] A pale image of all that appear even after blackboxing the whole process into aggregate production functions, via different elasticities of substitution and factor saving biases. A pertinent discussion is the cited work by Abramovitz (1993). Relatedly see also Nelson (1981).

Second, inducement may also take the form of an influence of market conditions upon the relative allocation of search efforts to different technologies or products**,** that is in the allocation of inventive efforts across different paradigms. . Note that while the former inducement process concerned the *directions* of search within a paradigm (e.g. in the inputs space or in terms of product characteristics), this second form regards the *intensity of search* and, other things being equal, the rates of advance, between paradigms. In the literature, it has come to be known as '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. While it is not *a priori* reason why the perception of demand opportunities should not influence the allocation of technological efforts, the general idea of 'demand-led' innovation has been criticized at its foundation for its theoretical ambiguities. (Does one talk about observed demand? Expected demand? And how are these expectations formed? Cf. Mowery and Rosenberg, 1979; Dosi, 1982; Freeman, 1982). The empirical evidence is mixed. Schmookler's empirical research has shown how changes over time in the sales of different kinds of products tends to be followed, with a short lag, by changes in patenting in the same direction. Thus the rise in the sales of automobiles and motorized tractors in the first half of the twentieth century, and the fall off in the use of horses for transportation and farm work, was accompanied by a large increase in patenting relating to the first two products, and a fall of patenting relating to horse shoes. However, the review in Freeman (1994) concludes that 'the majority of innovation characterized as 'demand led' … were actually relatively minor innovations along established trajectories', while as shown by Walsh (1984) and Fleck (1988), 'counter-Schmookler'-type patterns was [the] characteristic of the early stage of innovation in synthetic material, drugs, dyestuff, …' and robotics (Freeman, 1984, p.480). As emphasized by Freeman himself and by Kline and Rosenberg (1986), the major step forward here (mentioned already) is the abandonment of any 'linear' model of innovation (no matter whether driven by demand or technological shocks) and the acknowledgement of a co-evolutionary view embodying persistent feedback loops between innovation, diffusion and endogenous generation of further opportunities of advancement.

Both mechanisms of 'inducement' discussed so far ultimately rest on the ways production and market conditions and their change influence 'cognitive foci' and incentives, and in turn, the way the latter affect behavioral patterns – both in terms of search heuristics and allocation rules of those working to created new technology. However changing relative prices can easily 'induce' changes in the directions of the technical changes brought to practice by users/adopters of new technologies, even holding search behavior constant, via the selection of the (stochastic) outcomes of search itself. This is the *third* inducement process. Suppose the allocation of resources dedicated to search were invariant to changing relative prices. Even in this case, however, would-be innovations – being them new prediction techniques or new machines to be sold to a new firm – will be implemented/selected only if they will yield total costs lower than those associated with the incumbent techniques/machines. But the outcome of the comparison obviously depends on relative prices.

To summarize, one ought to disentangle three sources of ‘inducement’ related to (a) changes in microeconomic rules of search, affecting the direction of exploration in the notional opportunity space and the pattern of adoption of machine-embodied technical change within paradigms; (b) changes in the allocation of resources to search efforts (irrespectively of their ‘directions’ *across paradigms and lines of business*); and (c) market-induced changes in the selection criteria by which some techniques or products are compared with alternative varieties. An evolutionary interpretation does that in ways that easily allow for endogenous interactions (i.e. ‘co-evolution’) between the incentive structure (stemming from relative prices and demand patterns), on the one hand, and learning capabilities, on the other. In this respect, Gavin Wright (1997) is an excellent illustration of the point. Even in the case of mineral resources – i.e. the nearest one can get to a ‘naturally’ determined opportunity set – Wright shows that opportunities themselves have been the outcome of both public and private search efforts (see also David and Wright (1997)). Conversely, more conventional views of inducement, by making stronger commitments to both optimizing rationality and equilibrium, obscure – in our opinion – the distinctions between behavioral effects and system level (‘selection’) effects, and, together, render very difficult any account of the sector-specific and period-specific patterns of knowledge accumulation. The blackboxing under unobservable constructs like ‘elasticities of substitution’ in aggregate or sectoral production functions just helps to rationalize the dynamic outcome while obscuring the process driving it.

Of course, in the longer term major changes in the patterns of innovation are associated with the emergence of new technological paradigms. Thus the shift in inventive efforts from horse-driven carriages to automobiles and motor tractors can be regarded as the result of successful efforts to advance - an ensemble of new technological paradigms - associated with the successful development of e.g. gasoline engines, cheaper steel, electromechanical machine tools, etc. From this point of view, over such longer timescale it is the emergence and development of new technological paradigms that molds the direction as well as the rate of technological advance, rather than ‘inducement’ in any strict sense of such a notion.

6. Technological Regimes: Sectoral Specificities in Patterns of Technological Advance, and the Characteristics of Innovative Actors

An important area of investigation has concerned over the last three decades the identification of different patterns of industrial evolution conditional on specific regimes of technological learning. By ‘regimes’ here we mean distinct ensembles of technological paradigms with their specific learning modes and equally specific sources of technological knowledge. One of the aims of the well-known taxonomy by Keith Pavitt (1984) is precisely to capture such relations mapping 'industry types' and industry dynamics (see also Marsili, 2001, for important refinements). To recall, Pavitt taxonomy comprises four groups of sectors, namely

(i) 'supplier dominated', sectors whose innovative opportunities mostly come through the acquisition of new pieces of machinery and new intermediate inputs (textile, clothing, metal products belong to this category);
(ii) 'specialized suppliers', including producers of industrial machinery and equipment;
(iii) 'scale intensive' sectors, wherein the sheer scale of production influence the ability to exploit innovative opportunities partly endogenously generated and partly stemming form science based inputs .[19]
(iv) 'science based' industries, whose innovative opportunities co-evolve, especially in the early stage of their life with advances in pure and applied sciences (microelectronics, informatics, drugs and bioengineering are good examples).

Other, rather complementary, taxonomic exercises have focused primarily on some characteristics of the innovation process, distinguishing between a 'Schumpeter Mark I' and a 'Schumpeter Mark II' regime, dramatizing the difference between the views of innovative activities from Schumpeter (1911) and Schumpeter (1942): see Dosi *et al.* (1995), Breschi et al. (2000), Malerba and Orsenigo (1997), Marsili (2001). The Mark I regime is characterized by innovations carried to a good extent by innovative entrants and by relatively low degrees of cumulativeness of knowledge accumulation, at least at the level of individual firms. Conversely under the Mark II regime innovative activities are much more cumulative and undertaken to a greater extent by a few incumbents which turn out to be 'serial innovators'.

In our view, such taxonomic exercises are important in their own right in that they identify discretely different modes through which innovation occurs in contemporary economies. And they are also important because they allow a link between such modes of innovative learning, the underlying sources of knowledge, the major actors responsible for the innovative efforts and the ensuing forms of industrial organization. See Table 1 from Pavitt (1984) for one of such empirical attempts.

Different technological regimes are supported by distinct institutions governing public research and training and, at the market end, the interactions among producers. Such institutions, together with the corporate actors involved contribute to define distinct *sectoral systems of innovation and production*: see Malerba (2002 and 2004).

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[19] Here one should in fact distinguish between 'discontinuous' complex-product industries such as automobiles, white goods and other consumer durables vs. 'continuous' flow industries such as oil refining or steel making.

Table1. Sectoral technological trajectories: Determinants, directions and measured characteristics

Category of firm (1)		Typical core sectors (2)	Determinants of technological trajectories			Technological trajectories	Measured characteristics			
			Sources of technology (3)	Type of user (4)	Means of appropriation (5)	(6)	Source of process technology (7)	Relative balance between product and process innovation (8)	Relative size of innovating firms (9)	Intensity and direction of technological diversification (10)
Supplier-dominated		Agriculture; housing; private services traditional manufacture	Suppliers Research extension services: big users	Price sensitive	Non-technical (e.g. trademarks, marketing, advertising, aesthetic design)	Cost-cutting	Suppliers	Process	Small	Low vertical
Production intensive	Scale intensive	Bulk materials (steel, glass); assembly (consumer durables & autos)	PE suppliers: R&D	Price sensitive	Process secrecy and know-how: technical lags: patents: dynamic learning economies:	Cost-cutting (product design)	In-house: suppliers	Process	Large	High vertical
	Specialized suppliers	Machinery; instruments	Design and development users	Performance sensitive	design know-how; knowledge of users: patents	Product design	In-house: customers	Product	Small	Low Concentric
Science based		Electronics/ electrical; chemicals	R&D Public science; PE	Mixed	R&D know-how; patents: process secrecy and know-how; dynamic learning economies	Mixed	In-house: suppliers	Mixed	Large	Low vertical High concentric

[a] PE = Production Engineering Department.

Source: Pavitt (1984, p.12)

7. The Dynamic of Productive Knowledge, and the Dynamics of Production Coefficients

It is a rather straightforward consequence of the view of technology and innovation that firms ought to be expected to generally differ in the techniques they master. They are likely to differ in both the broad ‘recipes’ they use, and even when they use the same nominal recipe (with the same codified elements) they almost certainly will differ in the tacit aspects of those recipes. The way work on a particular technique is organized and managed almost never is the same across firms in the same nominal industry. Firms command and use different routines. Some important consequences this theoretical orientation which are quite at odds with traditional thinking in economics are the following.

a) In general, there is at any point in time one or very few best practice techniques which dominate the others irrespectively of relative prices.
b) Different firms are likely to be characterized by persistently diverse (better and worse) techniques.
c) Over time the observed aggregate dynamics of technical coefficients in each particular activity is the joint outcome of the process of imitation/diffusion of existing best-practice techniques, of the search for new ones, of the death of some others and of the changing shares of the incumbent ones over the total (these processes of course might or might not correspond to a similar dynamics in terms of *firms* which are so to speak the carriers of these techniques: see below).
d) Changes over time of the best practice techniques themselves are likely to display rather regular paths (i.e. trajectories) in the space of input coefficients.

Let us further illustrate the previous points with a graphical example.

Suppose that, for the sake of simplicity, we are considering here the production of an homogeneous good under constant returns to scale with two variable inputs only, x_1 and x_2.[20]

A paradigm-based theory of production predicts that, in general, in the space of unit inputs, micro coefficients are distributed somewhat as depicted in Figure 3. Suppose that at time t the coefficients are c_1 ..... c_n; where 1 . . . . . *n* are the various techniques labelled in order of decreasing efficiency at time *t*. It is straightforward, for example, that technique c_1 is unequivocally superior to the other ones no matter what relative prices are: it can produce the same unit output with less inputs of both x_1 and x_2. The same applies to the comparison between c_3 and c_n, etc.

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[20] Note that fixed inputs, vintage effects and economies of scale would just strengthen the argument.

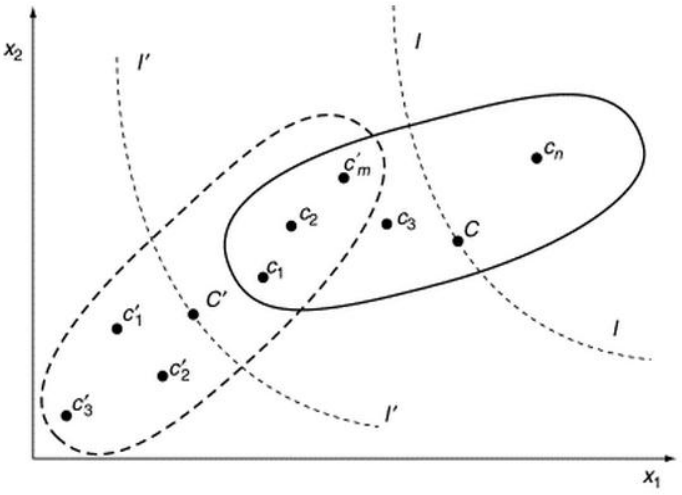

Figure 3. Microheterogeneity and technological trajectories

A rapidly expanding evidence robustly supports the existence of *wide* and *persistent* inter-firm and inter-plant asymmetries in production coefficients at all levels of disaggregation (cf. Nelson, 1981; Baily *et al.* 1992; Baldwin, 1995; Bartelsman and Doms, 2000; Bottazzi *et al.* 2007; Jensen and McGuckin, 1997; Power, 1998; Rumelt, 1991; Syverson, 2004; and Dosi, 2007).

Typically the support of inter-firm / inter-plant distribution of both labor productivities and 'total factor productivity'[21] are strikingly wide even at relatively high levels of sectoral disaggregation. So, for example, Syverson (2004) finds that at a four digit disaggregation, 'the average 90-10 and 35-5 percentile [labor] productivity rations within industries are over 4 to 1 and 7 to 1 respectively' (p. 535). Similar inter-firm dispersion at 3-digit disaggregation are found in the Italian industry by Bottazzi *et al.* (2007) and Dosi (2007). Moreover, such productivity differentials are quite stable over time with some mild regression-to-the-mean tendency (cf. Dosi, 2007). A similar picture emerges from all micro longitudinal data banks we are aware of. It is also important to notice that inter-firm / inter-plant differences in labor productivities are not accounted for by differences in relative factor intensities (cf. Syverson, 2004; preliminary elaborations by one of us on the Italian industry show that the within-industry / cross-firm correlations between labor productivities and output/capital ratios are basically nil). Interestingly, such widespread differences in production efficiency *across firms and across plants* continue to apply irrespectively of the degrees of sectoral disaggregation of the data. As Griliches and Mairesse (1997) put it

> 'we … thought that one could reduce heterogeneity by going down from general mixtures as 'total manufacturing' to something more coherent, such as 'petroleum refining' or 'the manufacture of

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[21] Notwithstanding the ambiguities of such latter measure, discussed in Dosi and Grazzi (2006)

> cement'. But something like Mandelbrot's fractal phenomenon seem to be at work here also: the observed variability-heterogeneity does not really decline as we cut our data finer and finer. There is a sense in which different bakeries are just as much different from each others as the steel industry is from the machinery industry.'

For evolutionary perspective, heterogeneity in the degrees of innovativeness and production efficiencies should not come as a surprise. A non-negligible part of the differences in production efficiencies must be due to different distributions of capital equipment of different vintages (the early intuition about the phenomenon is from Salter, 1962). However, broader differences are what one ought to expect to be the outcome of idiosyncratic capabilities (or lack of them), mistaken-ridden learning and path-dependent adaptation. Indeed, such an evidence is quite in tune with the view of technological evolution presented above: this is in fact what one ought to expect to be the outcome of idiosyncratic capabilities (or lack of them), mistaken-ridden learning and path-dependent adaptation.

Let us call this property *technological dominance,* and call some measure of the distribution of the coefficients across heterogeneous firms as the *degree of asymmetry* of that industry (for example, the standard deviation around the mean value C).

The first question is why doesn't the firm using the *n-th* adopt technique c_l? The simplest answer based on the foregoing argument is 'because it does not know how to do it...'. That is, even if it is informed about the existence of c_1, it might not have the capabilities of developing or using it. Remarkably, this might have little to do with the possibility for c_1 to be legally covered by a patent. The argument is much more general: precisely because technological knowledge is partly tacit, also embodied in complex organizational practices, etc., technological lags and lead may well be persistent even without legal appropriation. The opposite also holds: if the two firms have similar technological capabilities, imitation might occur relatively quickly, patent protection notwithstanding, by means of 'inventing around' a patent, reverse engineering, etc…

We are prepared to push the argument further and suggest that even if all firms were given the codified part of the recipe for technique c_1 (or, in a more general case, also all the pieces of capital equipment associated with it), performances and thus revealed input coefficients might still widely differ. It is easy to illustrate this by means of the foregoing cooking example: despite readily available cooking recipes, one obtains systematically asymmetric outcomes in terms of widely shared standards of food quality. Note that this has little to do even in the domain of cooking with 'variety of preferences': indeed, we are ready to bet that most eaters randomly extracted from the world population would systematically rank samples of English cooks to be 'worse' than French, Chinese, Italian, Indian ones, even when performing on identical recipes!!. If one accepts the metaphor, this should apply, much more so, to circumstances whereby performances result from highly complex and opaque organizational routines (Incidentally, Leibenstein’s X-efficiency rest also upon this widespread phenomenon).

Suppose now that at some subsequent time *t’* we observe the changed distribution of microcoefficients c'_3,..., c'_m,. How do we interpret such a change?

The paradigm-based story would roughly be the following. At time *t,* all below-best-practice firms try with varying success to imitate technological leader(s). Moreover, firms change their market shares, some may die and other may enter: all this obviously changes the weights (i.e. the relative frequencies) by which techniques appear. Finally, at least some of the firms try to discover new techniques, prompted by the perception of innovative opportunities, irrespectively of whether relative prices change or not (for the sake of illustration, in Figure 3, the firm which mastered the technique labeled 3 succeeds in leapfrogging and becomes the technological leader while *m* is now the marginal technique).

As discussed at greater length in Cimoli and Dosi (1995), and in several contributions to Cimoli *et al.* (2009), this interpretation of the distributions of techniques of production bears fundamental implications also in terms of international growth patterns. Consider again the illustration of Figure 3 and suppose that the evidence does not refer to two distributions of technical micro coefficients over time within the same country, but instead to two countries at the same time: after all, paraphrasing Robert Lucas, we only need informed tourists to recognize that most countries can be ranked in terms of unequivocal average technological gaps. The explanation of such international differences fundamentally rest upon the processes of accumulation of technological capabilities. Indeed, the economic discipline has undertaken far too few exercises at the highest available disaggregation on international comparisons among micro technical coefficients. Our conjecture is that less developed countries may well show higher utilization of all or most inputs per unit of output and perhaps even higher relative intensity of those inputs that conventionally would be consider more scarce (that is, some loose equivalent of what euphemistically the economic profession calls in international trade the Leontieff paradox). An evolutionary interpretation is straightforward: unequivocal technological gaps account for generalized differences in input efficiencies. Moreover, if technical progress happens to involve also high rates of saving in physical capital and skilled-labor inputs, one may also observe less developed countries which do not only use more labor per unit of output but also more capital per unit of labor input as compared to technological leaders (Figure 3 illustrates a similar case: compare for example, techniques c_3 and c_n).[22]

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[22] The models in Nelson (1968), and Nelson and Pack (1999), are congenial formalizations of productivity differences across nations that have these features. Dosi *et al.* (1990) and Cimoli and Soete (1992) present also formalizations of international trade flows driven by technology gaps across countries

8. Invention, Innovation, and Diffusion

Let us briefly consider how innovations diffuse in the economy.[23]

One of the contributions of J. Schumpeter's work that is often cited with reference to technological change concerns his distinction between invention, innovation, and diffusion. According to his definition, invention concerns the original development of some novel would-be process of production or product while innovation entails its actual introduction and tentative economic exploitation. Diffusion describes its introduction by buyers or competitors. It is a rough and 'heroic' conceptual distinction, which can hardly be found in practice, since the empirical processes are usually never precisely like this. The invention is often introduced from the start as an innovation by economically-minded research establishments. Diffusion entails further innovation on the part of both developers and users. All three activities are often associated with changes in the characteristics of, and incentives for, potential innovators/adopters. However, Schumpeter's distinction between invention, innovation, and diffusion is still a useful theoretical point of departure. For example, invention is suggestive of the sort of unexploited potential for technological progress whose sources we discussed above, while innovation and diffusion hint at the economically motivated efforts aimed at the incorporation of technological advances into economically exploitable products and processes.

The two major stylized facts already highlighted by Rosenberg (1976) are, *first* that diffusion is a time-consuming process, and, *second* that the speed varies widely across technologies and across countries. One should add two further properties, namely that, *third*¸ diffusion of successful innovations most often follows S-shaped, but asymmetric, profiles (Figure 4 illustrates all three points).

However, *fourth*, a good percentage of innovations, even when introduced by a small number of initial adopters, never diffuses and thus ultimately fail (hence also the sample selection bias stemming from considering only successful ones).

There are few basic ingredients which evolutionary analyses (of both the empirical and the theoretical kinds) share in the interpretation of diffusion dynamics. An obvious building block is the acknowledgement of the ubiquitous heterogeneity across would-be adopters on nearly every dimension which might think of as influencing adoption - ranging from sheer size all the way to different 'absorptive capacities' (Cohen and Levinthal, 1990) and abilities to use the new techniques, pieces of equipment and even consumption goods. Indeed, if one adds to adopters' heterogeneity also some dynamics in the characteristics of the good to be diffused, one goes a long way in accounting for the observed *retardation factors* in innovation diffusion (cf. David, 1990). The copious empirical literature estimating probit models of diffusion is well in tune.

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[23] See also Hall (2005) and Geroski (2000), and the older discussion from an evolutionary angle in Metcalfe (1988).

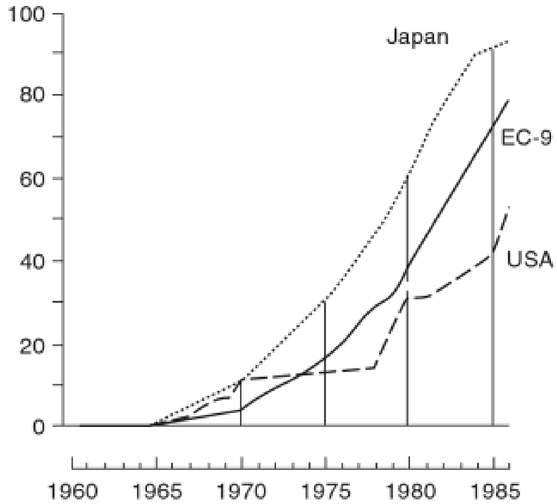

Figure 4. The diffusion of continuous casting of steel, as a percentage of total crude steel production

Source: Ray (1989, p.4)

On the supply side, heterogeneity is amply endogenous to the dynamics of learning, innovation, imitation, selection amongst producers (see the next section): products characteristics and their prices change and with that also the markets shares and the very identity of producers themselves.[24]

On the demand side, especially when the artifact to be diffused is a production good, learning-by-using is a powerful driver of diffusion. And, indeed, in evolutionary worlds, the ability to learn how to use and exploit new technologies is likely to be subject to unexpected bonanzas ad well as dire delusions (the model in Silverberg *et al.* 1988, highlights the point; discussions of the related 'cognitive biases' are in Dosi and Lovallo, 1997; and Gary *et al.* 2008). Conversely, the frequent requirements of organizational changes associated with the adoption of innovations, especially when the latter are producer goods, represent a powerful *retardation factor*, both with respect to adoption as such and to the reaping of its economic benefits (Brynjolfsson and Hitt, 2000, powerfully illustrate the point).

The process involves important collective dimensions as well, including knowledge spillovers, network externalities, endogenous evolution of preferences as well as sheer herd behaviors.

Can one identify different families of evolutionary processes of diffusion? An attempt to do so is in Nelson *et al.* (2004) where one distinguishes four 'archetypes' of diffusion patterns conditional on the presence/absence of dynamics increasing returns and of sharp persuasive

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[24] In fact diffusion in production is intimately intertwined with the process of imitation, generally ridden with improvements in the initiated artifact and in the techniques to produce it: an illustration of the point in the case of the steam engines in Rosenberg (1996).

feedbacks on the returns to adoption itself. Phenomena like fads belong to one extreme (absence on both dimensions), while QWERTY-type diffusion (David, 1985) belongs to the opposite one.

9. The Path Dependence of the Processes of Technological Evolution

Two quite general features of the processes of technological innovation discussed so far are dynamic increasing return, path dependency and their interaction.

Let us consider first the relationship between evolutionary success, intrinsic ‘fitness’, and chance (i.e. unpredictable historical events) in the development and diffusion of innovations.

Students of technical advance long have noted that, in the early stages of a technology history, there usually are a number of competing variants or even competing paradigms. This was the case of vehicles, some driven by the combustion engines, some by steam engines, some by batteries. As we know, gasoline-fuelled engines came to dominate and the other two possibilities were mostly abandoned. The standard interpretation for this is that gasoline engines were potentially superior and with time, trial-and-error and learning such superiority became manifest. There is however an alternative explanation grounded in the interaction between dynamic increasing returns of some kind, network externalities and path-dependency (cf. David, 1985; 1988, 2001b; and Arthur, 1988 and 1989). In this second interpretation the internal combustion engine need not have been innately superior. All that would have been required was that, because of a run of luck, it became heavily used or bought, and this started a rolling snowball mechanism fuelled by some sort of collective positive feedback.

What might be behind an increasing returns rolling snowball? Arthur, David, and other authors suggest several different possibilities. One of them is that the competing technologies involved are strongly cumulative technologies. In a cumulative technology, today’s technical advances draw from and improve upon the technology that was available at the start of the period, and tomorrow’s in turn build on today’s. So, in the case of the history of automobile engine technology - according to the cumulative technology interpretation - gasoline engines, steam engines, and electrical engines, all were plausible alternative technologies for powering cars, and it was not clear which of these means would turn out to be superior. Reflecting this uncertainty, different inventors tended to make different technological bets. Assume, however, that simply as a matter of chance (or marginal choice or political decision), a large share of these efforts just happened to focus on one of the variants – e.g. the internal combustion engine – and as a result, over this period there was much more overall improvement in the design of internal combustion engines than in the design of the two alternative power sources. Or, alternatively, assume that while the distribution of inventive efforts were relatively even across the three potential paradigms simply as a matter of chance significantly greater advances were made on internal combustion engines that on the other ones. But then, at the end of the first period, if there were a rough tie before, gasoline powered engines now are better than steam or electric engines. Cars embodying internal combustion engines will sell better. More inventors thinking about where to allocate their efforts now will be deterred from allocating their attention to steam or electric engines because large advances in these need to be achieved before they would become competitive even with existing internal combustion engines. Thus, there are many strong incentives for the allocation of inventive efforts to be shifted toward the variant of the technology that has been advancing most rapidly. The process is cumulative. The consequences of increased investment in advancing internal combustion engines, and diminished investment in advancing the other two power forms, are likely to be that the former pulls even further ahead. Relatively shortly, a clear dominant paradigm has emerged. And all the efforts to advance technology further in this broad area come to be concentrated on improving that particular paradigm.

There are two other largely complementary dynamic increasing returns stories. One stresses network externalities or other advantages to consumers or users if what different individuals buy are similar, or compatible, which lends advantage to a variant that just happened to attract a number of customers already. The other stresses systems aspects where a particular product has a specialized complementary product or service, whose development lends that variant special advantages. Telephone and computer networks, in which each user is strongly interested in having other users have compatible products, are commonly employed examples of the first case. Video cassette recorders which run cassettes that need to be specially tailored to their particular design, or computers that require compatible programs, are often used examples of the second. Paul David’s story (1985) of the reasons why the seemingly inefficient ‘QWERTY’ typewriter keyboard arrangement has persisted so long as a standard involves both its familiarity to experienced typists and the existence of typewriter training programs that teach QWERTY. As in the QWERTY story, the factors leading to increasing returns often are intertwined, and also linked with the processes involved in the development of cumulative technologies. Thus, to return to our automobile example, people who learned to drive in their parents’ or friends’ car powered by an internal combustion engine naturally were attracted to gas powered cars when they themselves came to purchase one, since they knew how they worked. At the same time the ascendancy of automobiles powered by gasoline burning engines made it profitable for petroleum companies to locate gasoline stations at convenient places along highways. It also made it profitable for them to search for more sources of petroleum, and to develop technologies that reduced gasoline production costs. In turn, this increased the attractiveness of gasoline powered cars to car drivers and buyers.

Note that, for those who consider gas engine automobiles, large petroleum companies, and the dependence of a large share of the nation’s transportation on petroleum, a complex that spells trouble, the story spun out above indicated that ‘it did not have to be this way’. If the toss of the die early in the history of automobiles had come out another way, we might today have had steam or electric cars. A similar argument recently has been made about the victory of A.C. over D.C. as the ‘system’ for carrying electricity (David, 1992). The story also invites consideration of possibly biased professional judgments and social or political factors as major elements in the shaping of long run economic trends. After all, in these stories all it takes may be just a little push.

It is difficult to precisely assess the importance and frequency of such path-dependent processes, since of course counterfactuals involving ‘running the tape of history another time’ are impossible (in social sciences but also in biology). Come as it may, evolutionary interpretations of technological change – and as we shall see of industrial dynamics and development – are deeply skeptical of any view of evolution as the inevitable unfolding of a process leading from the good to the better. Such a view tries to justify and explain any end-state of the system as being the best possible outcome given the (perceived) constraints by imperfectly informed but fully ‘rational’ agents along the whole path. The view, emphatically illustrated in Liebowitz and Margolis (1995) basically aims at rationalizing whatever one observes as an equilibrium and, at the same time, at attributing rational purposefulness to all actions which led to any present state.

On all that, David (2001b) and Dosi (1997) coincide in the rejection of any Panglossian interpretations of history as ‘the best which could have happened’, mainly ‘proved’ by the argument that ‘rational agents’ would not have allowed anything short of the optima to happen (compare the amazing similarities with dr. Pangloss’ remarks in Voltaire’s *Candide* on the virtues of Divine Providence).

10. Conclusions

The evidence on the drivers and processes of innovation discussed in this work witness the wealth of findings over the last half a century on the economics of innovation. However, many challenges are lying ahead.

Let me first mention a few by the way of a conclusion. First, the identification of the features of technological trajectories in a variety of sectors is far from over.

Second, and relatedly, one is only beginning to make the link between the dynamics of knowledge accumulation and the evolution over time in the distribution of the micro coefficients of production.

Third, there are profound links between the mature and dynamics of innovative knowledge and the nature and dynamics of corporate organizations: indeed the developments of a knowledge-based (or capability-based) theory of the firm are only in its infancy (more in Dosi *et al.* 2000; and Dosi *et al.* 2008).

Finally, an item high on the research agenda is a more detailed understanding (and also more accurate formal accounts) of the relationship between innovation, competition and the evolution of industries.

All this regarding the microeconomics of innovation and industrial dynamics. But, such microeconomics ought to be considered also at the core of an alternative microfoundation of macroeconomics, wherein multiple agents - heterogeneous on technological and behavioral grounds - interact (most likely) under far-from-equilibrium conditions yielding collectively the observed macrodynamics. (For some attempts in this direction, cf. Dosi *et al.* 2010 and Dosi *et al.* 2013).

A tall and exciting agenda indeed.

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