Chapter 3

TECHNICAL CHANGE AND INDUSTRIAL DYNAMICS AS EVOLUTIONARY PROCESSES

GIOVANNI DOSI* *AND* RICHARD R. NELSON†

**Laboratory of Economics and Management*

Sant'Anna School of Advanced Studies

Pisa, Italy

†*Institute for Social and Economic Research and Policy*

Columbia University, New York

New York, USA

Contents

Handbooks in Economics, Volume 01

DOI: 10.1016/S0169-7218(10)01003-8

Abstract

This chapter reviews and integrates much of what has been learned on the processes of technological evolution, their main features, and their effects on the evolution of industries.

First, we map and integrate the various pieces of evidence concerning the nature and structure of technological knowledge, the sources of novel opportunities, the dynamics through which they are tapped, and the revealed outcomes in terms of advances in production techniques and product characteristics. Explicit recognition of the evolutionary manners through which technological change proceeds has also profound implications for the way economists theorize about and analyze a number of topics central to the discipline.

One is the theory of the firm in industries where technological and organizational innovation is important. Indeed a large literature has grown up on this topic, addressing the nature of the technological and organizational capabilities which business firms embody and the ways they evolve over time. Another domain concerns the nature of competition in such industries, wherein innovation and diffusion affect growth and survival probabilities of heterogeneous firms. The processes of knowledge accumulation and diffusion involve winners and losers, changing distributions of competitive abilities across different firms, and, with that, changing industrial structures. Both the sector-specific characteristics of technologies and their degrees of maturity over their life cycles influence the patterns of industrial organization—including size distributions, degrees of concentration, relative importance of incumbents and entrants, etc. This is the second set of topics which we address.

Finally, in the conclusions we briefly flag some fundamental aspects of economic growth and development as an innovation-driven evolutionary process.

Keywords

innovation, technological paradigms, technological regimes and trajectories, evolution, learning, capability-based theories of the firm, selection, industrial dynamics, emergent properties, endogenous growth

JEL classification: O30, O31, O32, O33, L16, L20

1. Introduction

A wide ensemble of scholars, in both economics and several other disciplines, have been studying technological advance, viewed as an evolutionary process. This perspective on technological change is closely linked to recent research on industrial dynamics and on economic growth as processes intertwined with and driven by technological and organizational innovation. In this chapter, we lay out the basic premises of this research and review and integrate much of what has been learned on the processes of technological evolution, their main features, and their effects on the evolution of industries.[1]

The proposition that technology advances through an evolutionary process is not a new idea. Nearly 300 years ago, Bernard de Mandeville, pointing to what he regarded as one of the most complex and sophisticated artifacts of his era, the (then) modern Man of War [the warship], explained how its design came about this way:

> *"What a Noble as well as Beautiful, what a glorious Machine is a First-Rate Man of War. . . .We often ascribe to the Excellency of Man's Genius, and the Depth of his Penetration, what is in reality owing to the length of Time, and the Experience of many Generations, all of them very little differing from one another in natural Parts of Sagacity." (Mandeville, 1714, vol. II, pp. 141–142)*[2]

Note also that Adam Smith begins *The Wealth of Nations* by highlighting the importance of technological advance to economic growth, and discusses the processes involved in a way that anticipates modern evolutionary analyses. In his interpretation of the factors behind the enormous improvements in workers' productivity—in general, and in his pin making example, in particular—Smith proposes that a key driving force has been:

> *". . .the invention of a great number of machines which facilitate and abridge labour, and enable one man to do the work of many." (Smith, 1776, p. 17)*

In turn,

> *"a great part of the machines 'made use of' in those manufactures in which labour is most subdivided were originally the invention of common workmen, who being each of them employed in some very simple operation, naturally turned their thoughts toward finding easier and readier methods of performing it." (Smith, 1776, p. 20)*

Together,

> *"many improvements have been made by the ingenuity of the makers of the machine. . .and some by that of those who are called philosophers or men of speculation, whose trade it is, not to do anything but to observe everything; and who, upon that account are often capable of combining together the powers of the most distant and dissimilar objects." (Smith, 1776, p. 21)*

[1] Earlier reviews and discussions in a germane spirit upon which we build are Dosi (1988, 1991, 1997), Cimoli and Dosi (1995), Dosi and Nelson (1994), Dosi et al. (2005b), Nelson (1981, 1996, 1998, 2005), Freeman (1982, 1994), Nelson and Winter (1977, 2002), and Dosi and Winter (2002); more specifically on evolutionary theories of economic growth, see also Silverberg and Verspagen (2005b), and on evolutionary models within an ACE modeling perspective, see the detailed survey in Dawid (2006).

[2] On Mandeville as a precocious evolutionary economist, see Rosenberg (1963).

The processes through which "modern" warship design came to be and productivity was improved, both via "learning by doing"—we would say nowadays—and through the development of new machines, that Mandeville and Smith are suggesting clearly are "evolutionary," in the broad sense of the term that we will develop shortly.

To return to Mandeville's discussion of the evolution of the design of the modern battleship, he does not deny the purpose and competence of those who are designing warships at any time. On the other hand, he clearly is denying that the state of the art in this arena at his time was the result of great sagacity and creativity on the part of a small number of individuals, much less coherent rational planning, and proposing rather that it was the product of many minds and many generations of designers, each working somewhat myopically, with later generations building on the achievements and learning from the mistakes of earlier ones.

That is, Mandeville, as most contemporary scholars analyzing technological advance as an evolutionary process, departs from any assumption of strong "rationality," in the sense either of a fully informed global scan of alternatives made by inventors at any time, or accurate forward-looking technological expectations. The ubiquitous presence of drivers of behavior distinct from strong rationality in the above sense will be indeed a first recurring evolutionary theme in the interpretations of technological and economic change that follow.

A second theme well in tune with evolutionary ideas which will repeatedly appear in our discussion is the emphasis on disequilibrium dynamics as a general feature of "restless capitalism," as Stan Metcalfe put it. As in the case of Smith's "practical men" and "philosophers", the search for new techniques of production and new products (as well as many other economic behaviors—including investment, pricing, production decisions) most often entail trials and errors, gross mistakes, and unexpected successes. This applies also to industrial organization and industrial change: also at this level of analysis, an evolutionary perspective focuses upon the processes by which firms persistently search for and adopt new technologies as well as new organizational forms and new behavioral patterns as means of gaining advantages over their competitors, and upon the features of the competitive process driving the growth, the decline and possibly the disappearance of various firms.

A third theme regards the identification of the regularities in the processes of technological and industrial change, notwithstanding the lack of an *ex ante* commitment to any equilibrium notion. For example, can we identify some relatively invariant patterns in the processes of innovation? How are innovations selected? What are the relationships between technologies and forms of corporate organization? And between technical change and forms of competition? How can one characterize the ways through which relatively orderly processes of industrial change emerge out of underlying "disequilibrium" behaviors? What is the relative role of "chance" and "necessity" in evolutionary processes, and relatedly, to what extent is techno-economic evolution path-dependently shaped by events occurring along its historical unfolding? In which ways do institutions and policies embed the processes of technological and economic change?

Come as it may, as Freeman (1982) already noted, since the classics not much progress had been made for almost two centuries in our understanding of the ways new technical knowledge is generated and its impact works through the economy. Karl Marx and Joseph Schumpeter stand out as major exceptions, but they were rather lonely voices.[3] The importance of technological change reappeared, almost

[3] Alfred Marshall too offered rich insights into the evolution of industries even if the subsequent systematization of his contribution builds on an equilibrium skeleton.

by default, in Robert Solow's growth analysis in the 1950s, but it is only over the last 40 years that one has systematically started looking—using the felicitous expression of Nate Rosenberg—inside the "blackbox of technology," investigating the sources of novel opportunities, the dynamics through which they are tapped and the revealed outcomes in terms of advances in production techniques and product characteristics. The first part of this chapter maps and integrates such pieces of evidence. Explicit recognition of the evolutionary manners through which technological change proceed has also profound implications for the way economists theorize about and analyze a number of topics central to the discipline.

One is the theory of the firm in industries where technological innovation is important. Indeed a large literature has grown up on this topic, addressing the nature of the technological and organizational capabilities which business firms embody and the ways they evolve over time.

Another domain concerns the nature of competition in such industries, wherein innovation and diffusion affect growth and survival probabilities of heterogeneous firms, and, relatedly, the determinants of industrial structure. The processes of knowledge accumulation and diffusion involve winners and losers, changing distributions of competitive abilities across different firms, and, with that, changing industrial structures. Both the sector-specific characteristics of technologies and their degrees of maturity over their life cycles influence the patterns of industrial organization—including size distributions, degrees of concentration, relative importance of incumbents and entrants, etc. This is the second set of topics which we shall address below.

Third, the full acknowledgment of technical change as an evolutionary process bears distinct implications also for the understanding of the processes of economic growth, fuelled as they are by technological and organizational innovation. The "physiology" of modern capitalism rests on the evolution of multiple technologies and industries coupled with each other via input–output and knowledge flows. Some sectors shrink, others expand, yet other new ones appear generally associated with the emergence of radically new technologies. Overall, the patterns of growth of modern economies—with both their secular increase in per-capita productivity and incomes and their fluctuations and discontinuities—are deeply shaped by the underlying patterns of technological and organizational evolution. In Section 5, we shall offer some comments on these points.

The foregoing domains of analysis define also the structure of this work, which will start from some basic notions on the nature of technologies (Section 2) and the analysis of how technologies evolve (Section 3) together with a brief discussion of how technologies are embedded into business organizations and of the implications of all that for the theory of the firm (which is discussed from the angle of strategic management in Chapter 16). Next, we will explore the coupled dynamics of technological change and industrial evolution (Section 4). Finally, in Section 5, we shall briefly flag some fundamental aspects of economic growth and development as an innovation-driven evolutionary process.

First of all, to set the stage we need to briefly discuss what we mean by "technology."

2. On the nature of "technology"

In the most general terms, a technology can be seen as a human designed means for achieving a particular end—being it a way of making steel like the oxygen process, a device to process information such as a computer, or the ensemble of operations involved in heart surgery. These means most often entail particular pieces of *knowledge*, *procedures*, and *artifacts*. These different aspects offer different but complementary ways of describing technologies.

2.1. Technology and information

What are the characteristics of technological knowledge?

It is useful to take as starting points some very basic features shared by technological knowledge and *information*, in general.[4]

First, technological knowledge (even when taken to be equal to information) is nonrivalrous in use. Use by one economic agent in no way by itself reduces the ability of other economic agents to use that same knowledge.

Second, there is an intrinsic indivisibility in the use of information (half of a statement about whatever property of the world or of a technology is not worth half of the full one: most likely it is worth zero).

Third, both technological knowledge and sheer information involve high up-front generation cost as compared with lower cost in their repeated utilization, when the technology is "in place" (with "being in place" roughly meaning "with practitioners and organizations actually mastering and using it"). Moreover, information *stricto sensu* typically displays negligible cost of reproduction, which closely relates (but is not identical) to the proposition that information can be used on any scale (greater or equal than one). In fact, there is something genuinely special of information in general and also of technical knowledge in that they share a sort of notional *scale-free* property. So, in a first approximation (not to be taken too literally: see below), an "idea" when fully developed does not imply any intrinsic restriction on the scale of its implementation. In a language which we do not particularly like, were there a "production function" with information as the only input, it would display an output equal to zero for an information below "one unit" and a vertical line for information equal one.[5]

Fourth, as a consequence, there is a fundamental increasing returns property to the use of information and technological knowledge. The use of standard economic goods, ranging from shoes to machine tools, implies that use wears them out. This does not apply either to information or to technological knowledge. On the contrary, the persistent use of either implies at the very least its nondepreciation, at least in technical terms (their economic value is a different matter).

Indeed, important branches of contemporary economic theory are finally beginning to take on board the implications of having information as a fundamental input in all economic activities: other chapters in this Handbook address the advances in the fields such as "new growth" and "new trade" theories, informational externalities, and standard setting, incorporating increasing returns implications which the economic use of information intrinsically imply.[6] And such exploration is far from over.

[4] For the basics and several ramifications of the economics of information, see Arrow (1962a), Nelson (1959), Simon (1962), Akerlof (1984), Greenwald and Stiglitz (1986), and Radner (1992, 1993) among others.

[5] Compare with Romer (1994) for a discussion of the implications for (new) growth theories.

[6] The properties of information and its distribution—most likely imperfect, incomplete and asymmetric—across a multiplicity of economic agents bears also fundamental macroeconomic consequences which cannot be explored here: however the interested reader may appreciate the intuitive compatibility between analyses such as Greenwald and Stiglitz (1986) and Stiglitz (1994), on the one hand, and the microeconomics of production, competition, and economic change put forward in this chapter, on the other.

Notice also that even neglecting the features of technologies which are different from pure "information" (on which more below), the nonrival use, upfront generation cost, and indivisibility characteristics of the latter bear far-reaching implications for any theory of economic coordination and change. As Arrow (1996) emphasizes:

> *"[c]ompetitive equilibrium is viable only if production possibilities are convex sets, that is do not display increasing returns," but ... "with information constant returns are impossible" (p. 647). "The same information [can be] used regardless of the scale of production. Hence there is an extreme form of increasing returns." (p. 648)*

Needless to say, a fundamental consequence of this statement is the tall demand of providing accounts of economic coordination which do not call upon the properties of competitive equilibria. We shall see later the progress done by evolutionary-inspired theories.

Granted the foregoing properties of technology/information, technological knowledge has important characteristics of its own, highlighted by a body of interpretation pioneered in the 1960s and 1970s by Christopher Freeman in the United Kingdom and a few scholars in the United States, which could be called the "Stanford–Yale–Sussex (SYS) synthesis" (cf. Dosi et al., 2006b) based on the locations where at the time most of the major contributors were based. In brief, such an interpretation takes on board the basic intuitions on the economics of information already present in Arrow (1962a) and Nelson (1959), and further refinements (cf. David, 1993, 2004 among a few others), together with works focusing on the specific features of technological knowledge (including Dosi, 1982, 1988; Freeman, 1982, 1994; Freeman and Soete, 1997; Mowery and Rosenberg, 1989; Nelson, 1962, 1981; Nelson and Winter, 1977, 1982; Pavitt, 1987, 1999, 2005; Rosenberg, 1976, 1982; Winter, 1982, 1987, 2005, 2006a). In such a synthesis, one fully acknowledges some common features of information and knowledge—in general, and with reference to scientific and technological knowledge in particular. Together, however, one also distinguishes the specific characteristics of technological knowledge and of the ways it is generated and exploited in contemporary economies.

In the case of technology, it may well be that even if a body of knowledge might be *notionally* utilizable on any scale (say, a production process which can be applied ten or a million times), this does not imply that replication or imitation is necessarily easy and cheap (see Winter, 2005, 2006a; Winter and Szulanski, 2001, 2002). As we shall see at greater detail below, in the case of technological knowledge the "scale-free reproduction property" is subject to three major qualifications.

Certainly, *first*, the nonrivalry in use implies *nondepletability by reproduction or by transfer* of both scientific and technological knowledge: of course Pythagoras' theorem is depleted neither by repeated use by Pythagoras himself nor by learning on the part of his disciples. This property, however, is quite distinct from the easiness and costs of replication: this applies to the costs of teaching the theorem itself and, more so, to technological knowledge, concerning, say, the fine working of a plant *even within the same firm.*

Second, scientific and, even more so, technological knowledge share, to different extents, some degrees of *tacitness* (more on it below). This applies to the pre-existing knowledge leading to any discovery and also to the knowledge required to interpret and apply even codified information after it is generated. As Pavitt (1987) puts it with regards to technological knowledge:

> *"most technology is specific, complex...[and] cumulative in its development... It is specific to firms where most technological activity is carried out, and it is specific to products and processes, since most of the expenditures is not on research, but on development and production*

engineering, after which knowledge is also accumulated through experience in production and use on what has come to be known as 'learning by doing' and 'learning by using'." (p. 9)

Moreover,

"the combination of activities reflects the essentially pragmatic nature of most technological knowledge. Although a useful input, theory is rarely sufficiently robust to predict the performance of a technological artefact under operating conditions and with a high enough degree of certainty, to eliminate costly and time-consuming construction and testing of prototype and pilot plant." (p. 9)

Notice that given these features of technological knowledge, equating it to a *pure* "public good" might be quite misleading. While the characteristic of being nonrivalrous in use means that there are significant benefits to society as a whole if developed technologies were open for all to try to master and employ, even when there are no explicit barriers to use, there usually are non trivial costs to acquiring the relevant capabilities (see below on technological heterogeneity among firms, bearing far-reaching implications also in terms of growth and development theories).

The easiness and cost of replication across diverse economic actors is generally positive, often quite significant, and varies a lot too. In fact, as we shall see, the conditions and costs for replicability and imitation are important distinguishing marks of different technologies. Hence, in the technological domain the "scale-freeness" should not be taken too literally: "scaling-up" is by itself a challenging learning activity, often associated with the quest for economies of scale (see Section 3 on technological trajectories, and Winter, 2008).

Knowledge differs from sheer information in its *modes and costs of replication* (see Winter and Szulanski, 2001, 2002; for insightful discussions). While the metaphor of "reproduction of ideas" is just pushing a button on the computer with the instruction "copy" and possibly "send," the replication of technological knowledge concerning processes, organizational arrangements, and products is a painstaking and often quite expensive business (see Mansfield et al., 1981 among others). The bottom line is that even when there is an *Arrow core*, as Winter and Szulanski (2002) put it, in the sense of an informationally codifiable template, the actual process of reproduction involves significant efforts, costs, and degrees of uncertainty about the ultimate success—all linked also with the tacit elements involved in technological know-how.

All this bears important consequences also in terms of the theory of production.[7] The divisibility axiom is certainly not on the cards as a plausible assumption, in that even "ideas"—let alone "technologies"—bear the mark of "indivisibility": "half an idea"; to repeat, is certainly not of half the usefulness of a whole idea. And, together, technologies are ridden with indivisibilities of machines, plants, headquarters, etc. Conversely, "additivity"—under some important caveats—may stand (much more in the insightful discussion by Winter, 2008).

As Winter (1987) suggests, taxonomies based on different degrees of tacitness together with other dimensions provide a useful interpretative grid by which to classify different types of knowledge.

Tacitness refers to the inability by the actor(s), or even by sophisticated observers, to explicitly articulate the sequences of procedures by which "things are done," problems are solved, behavioral patterns are formed, etc. (see Dosi et al., 2005a; Nelson and Winter, 1982, especially Chapter 4; Polanyi, 1967, and the

[7] For more details, see Winter (1982, 1987, 2005), Nelson (1981), and Dosi and Grazzi (2006) among others.

references therein). In a nutshell, tacitness is a measure of the degree to which "we know more than we can tell."[8] In turn, the different degrees of tacitness of particular bodies of knowledge and the dynamics of knowledge codification bear ramified implications in terms of patterns of innovation, division of labor and presence/absence of "markets for technology." For example, interorganizational division of labor often requires a good deal of codification of "who does what," and even more codification is needed for the existence of a market for technologies, if by that we mean a market for pieces of knowledge which can be put to use by someone other than the originator of the technology itself, and which can be an object of negotiation and exchange (Arora and Gambardella, 1994; Arora et al., 2002; Granstrand, 1999; Chapter 15 in this handbook).

More generally, technological activities draw upon specific elements of knowledge, partly of the know-how variety and partly of a more theoretical kind. In fact as we shall see below, important advances have been made over the last quarter of a century in the identification across different technologies of (a) the *characteristics* of such knowledge—for example, to what extent is it codified and openly available in the relevant professional communities as distinct from the tacit skills of the actors themselves—and (b) its *sources*—does it come from external institutions such as universities and public laboratories, from other industrial actors such as suppliers and customers, or is it endogenously accumulated by the people and organizations who actually use it.[9]

Regarding the sources of technological knowledge, the reconstruction of the diverse institutional origins of novel learning opportunities helps also in going beyond any first, very rough, representation of "endogenous" versus "exogenous" technical progress. For the time being, let us stick to the basic notion that in no technological activity "knowledge drops for the sky." Even in the most science-based sectors, a good deal of technological advances are endogenously generated by more "applied," task-focused organizations. At the same time most if not all of the activities which have experienced the highest rates of technological progress, at least over the last half-century, are also those which have been also fuelled by "exogenous" scientific advances.

To understand both the nature and the dynamics of technological knowledge, a crucial step regards the understanding of *where technological knowledge resides* and how it is expressed, stored, improved upon (see Section 3). In that, the account of technology in terms of pieces of knowledge, their combinations and their changes has to be complemented by a more operational representation of *technology in action*.

2.2. Technologies as recipes

The conception, design, and production of whatever artifact or the completion of whatever service generally involves (often very long) sequences of cognitive and physical acts. Hence, it is useful to think of a technology also like a "recipe" entailing a design for a final product, whenever there is a final

[8] On the possibilities, obstacles and determinants of "tacitness reduction" via knowledge codification, in general and with reference to contemporary technologies, see Cowan (2001), Cowan et al. (2000), Nelson (2003), Nightingale (2003), and Pavitt (1987, 1999). More specifically on the contemporary patterns of codification of manufacturing technologies based on ICT instrumentation and computing, see Becker et al. (2005), Balconi (2002), and Lazaric and Lorenz (2003) among others. A more specific illustration in the case of the software industry is in Grimaldi and Torrisi (2001).

[9] A further distinction still largely unexplored, regards the *codification of learning processes* as distinct from the codification of search *outcomes*: see the insightful discussion in Prencipe and Tell (2001).

physical artifact—such as in the cookbook case—together with a *set of procedures* for achieving it. The recipe specifies a set of actions that need to be taken to achieve the desired outcome, and identifies the inputs that are to be acted on, and any required equipment (if sometimes implicitly). Where a complex physical product or artifact is the end of the procedure or a basic element of it, that artifact itself may be considered a technology, a view we will consider later in this section. Thus Mandeville's Man of War can be considered as a piece of technology. By the recipe view, so would be the way of building that ship. And quite sophisticated technologies, in the sense of the required procedures, might be involved also in sailing and using it effectively as a "Man of War."

The recipe specifies the sequence of procedures that are "legal," at the very least in the sense that they are technically feasible and apt to allow the desired outcome. In that respects, acts like "break the eggs smashing them with the pan over the sink" are not "legal" in the cake-making procedures in that they will never yield eventually a cake. As such, (well-constructed) recipes obey to sorts of *grammars* which prescribe what can or cannot be done on the ground of particular knowledge bases. Recipes are *coded programs* instructing on the sequential combinations of physical and cognitive acts, along the sequence involving various material inputs and machine services.[10]

The *technologies as recipes* view offers an enormous progress in the understanding of what technological knowledge is all about as compared to the blackboxing entailed by any representation of the kind cake $= f$(list of ingredients). Moreover, as we shall see below, the recipe view offers promising angles also to the formal representation of the dynamics of problem-solving procedures involved in any technological activity, However, recalling our earlier discussion of technologies as knowledge it is important to recognize that recipes have tacit aspects as well as articulated ones, and that the written-down recipe, what we call the codified recipe, is far from the whole story. Tacit knowledge is precisely what is not (or, sometimes cannot even in principle) be conveyed in the codified recipe itself, but—in the example of the cake recipe—remains in the head (or better in the practice) of grandmothers and French cooks, and is transmitted more by example than by instruction. There is a general principle here: *no good artifact or service comes out of codified recipes alone* (for a detailed discussion, see Winter, 2006a). Or, putting the other way round, there is much more knowledge in technological procedures than any codified recipe can reveal.

In some cases, like the literal example of cooking recipes, one single person embodies the whole set of skills necessary to lead from the raw inputs to the final output, involving, say, how to break the eggs, mix them with flour, put the butter in the pan, etc., all the way to the final production of a cake. However, in the domain of industrial technologies this is not generally the case: the various pieces of knowledge and skills are distributed across many individuals and a crucial issue concerns when and how they are called for. Such a procedural, know-how centered, interpretation of technologies brings into sharp view the blurry lines between, or, better, the intertwining of technology, division of labor, organization, and management: more below. Thus if one considers the "recipe" for building a Man of War, or for sailing it, or for designing it, generally more than one person is involved, and this is so

[10] On the representation of "technologies as codes," see Baldwin and Clark (2000). It also worth mentioning the *funds-flow* theory of production which, while falling short of an explicit procedural representation of production activities, attempts to nest the use of inputs into an explicit temporal sequence flagging when the inputs themselves are used (i.e., when the flows of their services are called upon): cf. Georgescu-Roegen (1970) and the reappraisal, refinements, and applications in Morroni (1992).

regardless of whether complex artifacts are employed as production inputs: no matter how mechanized (as it is in contemporary times), the building of a ship is a team operation. Different people, and groups, are assigned different parts of the process. In fact technologies very rarely are just individual activities of sheer manipulation of physical objects. Rather, they involve intrinsic social elements, nested in particular organizations, and ensembles of them, which have led one of us to suggest the notion of *social technologies* (Nelson and Sampat, 2001), meant to capture the system of norms, beliefs, and social practices shaping the "ways of doing things." In turn, how Mandeville's ship turns out will depend not only on the overall ship design and recipe that nominally is being followed, but also on "social technologies" governing how the work is divided, the match up of the skills and understandings of what is to be done under that division of labor with what actually needs to be done, and how effectively the work is coordinated and managed.

2.3. Technologies as routines

The term "routines" has been proposed to recognize and denote the multiperson nature of the way organizations "make or do things": see Nelson and Winter (1982), Cohen et al. (1996), Teece et al. (1997), Dosi et al. (2000), the special issues of *Industrial and Corporate Change* edited by Augier and March (2000) and by Becker et al. (2005), Montgomery (1995), Becker and Lazaric (2009), and Foss and Mahnke (2000). A routine that is commanded by an organization is "an executable *capability* for repeated performance in some *context* that has been *learned* by an organization" (Cohen et al., 1996, p. 683). Routines, as thoroughly argued in Nelson and Winter (1982), (i) embody a good part of the memory of the problem-solving repertoires of any one organization; (ii) entail complementary mechanisms of governance for potentially conflicting interests (for more detailed discussions, see Cohen et al., 1996; Coriat and Dosi, 1998); and (iii) might well involve also some "meta-routines," apt to painstakingly assess and possibly modify "lower-level" organizational practices (the more incremental part of R&D activities, and recurrent exercises of "strategic adjustment," are good cases to the point).

Routines involve multiple organizational members who "know" how to appropriately elicit an action pattern or a signal in response to the specific environmental circumstances:

> *"Each individual is constantly engaged in receiving signals from other members of the organization or from the environment, responding to the signal with some operation from his repertoire, and thereby creating a signal for other members of the organization, or an effect in the environment. Here, the incoming signal might be the appearance of a partially finished automobile on a production line, the operation may be tightening particular screws and the outgoing 'signal' is the slightly-more-finished automobile going down the line. Or, the incoming signal may be a report summarizing last month's expense account submissions from the sales force, the operation may be a comparison with standards and past experience, and the outgoing signal a letter of protest." (Winter, 2006a, p. 134)*
>
> *"'Knowing your job' in [the] organization is partly a matter of having the necessary repertoire of actions, and partly knowing which actions go with which incoming signals. Each individual has some ability to perform a considerably larger set of actions than are called for in his job, but to the extent that 'practice makes perfect' he will acquire superior skill in the ones actually called for." (Winter, 2006a, p. 134)*

Note that the "program" built into routines generally involves, at the same time, recipes which tend to be silent regarding the division of labor, together with particular divisions of labor, plus specific modes of coordination: in the language introduced earlier, the former aspect primarily captures the "physical" technology involved, while the latter entails specific "social technologies" (Nelson and Sampat, 2001).

In turn, ensembles of organizational routines are the building blocks of distinct organizational competences and capabilities. In the literature, the two terms have often been used quite liberally and interchangeably. In the introduction to Dosi et al. (2000, 2008a), it is proposed that the notion of capability ought to be confined to relatively purposeful "high-level" tasks such as, for example, "building an automobile" with certain characteristics, while "competences," for sake of clarity, might be confined to the ability to master specific knowledge bases (e.g., "mechanical" or "organic chemistry" competences). Clearly, such notion of competences/capabilities largely overlaps with what has come to be known as the "competence view of the firm" (cf. Helfat et al., 2007; see also below and Chapter 19).

2.4. Technologies as artifacts

The *procedure-centered* representation of technology is highly complementary to what we could call an *artifact-centered* account of what technologies are and their dynamic over time (see Arthur, 2007; Baldwin and Clark, 2000; Basalla, 1988; Frenken and Nuvolari, 2004 among others). Indeed, recipes often involve *designs* of what it is there to be achieved as a final output. (Although not always: think of services such as airline booking system or a surgical operation.) Even when the procedure involves a notion of design, the latter is in general only one of the many possible configurations which can be achieved on the grounds of any one knowledge base. In fact, when outputs are physical artifacts, it is useful to study their dynamics in the *design space* (Bradshaw, 1992; Frenken and Nuvolari, 2004), defined by the properties of the components which make up the final output and their combinations. So, in the case of the warship, the technology—seen as a complex product system (Helfat, 2003; Prencipe et al., 2003)—is made in turn of components—the hull, the sailing apparatus, the guns, etc., held together by binding technical consistency conditions.[11] Further, dynamically, innovation can be fruitfully studied in terms of modifications and improvements of the performance characteristics of each components and the system as a whole. After all, the numerous discontinuities in naval history from the "Man-of-War" of Mandeville's times to the contemporary USS air carrier *Ronald Reagan* map into the dynamics of both "incremental" change and more radical ruptures in the structure and functionalities of the artifacts: these are precisely two central concerns of evolutionary theories of innovation.

The artifact angle on technologies is in fact useful for a rather general purpose, namely the identification of the techno-economic characteristics of specific final products on the one hand, and of machines, components, intermediate inputs, on the other. Hence, as we shall see, the history of technologies can be usefully tracked, from one angle, through the dynamics of outputs in their appropriate characteristics space. This is also the "hedonic" dimension of product innovations. Symmetrically technological advances are reflected by the specific performances of particular pieces

[11] Visitors of Stockholm can still admire a beautiful seventeenth-century warship, the *Vasa*, immaculately conserved because it almost immediately sunk, due to the King's interventions on the design which made it violate precisely those conditions.

of equipment (e.g., how fast can this cutting machine cut? What is the tolerance of that boring machine? How many bits of information can this computer process per second? etc.).

2.5. Knowledge, procedures, and input/output relations

Note that in a *procedural view* of technology, the orienting focus is not immediately the list of inputs and equipment used to produce, say, a semiconductor with certain properties, but rather it rests in the design of the devices, and the procedures used in the transformation of the raw silicon into a microprocessor; not on the quantities of iron, plastic, and copper that go into an automobile of specified characteristics, but rather on the design of the automobile and the procedures used to produce it. Concerning technological advance, modifications and refinements of procedures and designs are "where the action is," while changes in input/output relations are in a way the byproduct of successful attempts to achieve effective procedures and designs with certain performances and to change them both in desired directions. Thus, students of the theory of production should notice that what comes under the heading of "production functions" of whatever kind, is basically just the *ex post* descriptions of what appears in the "quantity part" of the recipe—in the foregoing cooking example, the amount of eggs, butter, flour, pans, electricity, human labor, that goes into the production of a cake—but such quantities themselves derive quite strictly from the nature of the recipe and the characteristics of the final product one is meant to obtain. So, for example, procedures involving 90% eggs and 10% flour are not "legal" (they are not part of an admissible procedure), because they will yield at most an omelette, and not a cake, *irrespectively of relative prices*.

Note also that, dynamically, in most cases efforts to change recipes directly entail changes in input characteristics and "intensities" and, conversely, attempts to substitute one input for another involve changes in production procedures. Good examples of the former are, in economic history, the changes in "capital intensity" associated with the "taylorist" and "fordist" transformation of business firms—roughly a century ago—as such an attempt of major proportions to change the "ways of doing things" within organizations. Symmetrically, attempts to "substitute more expensive inputs"—so easy when seen from the angle of some "production function"—often require the painstaking search of new recipes and effective procedures.

A question with crucial ramification for any theory of production regards precisely the mappings between *procedure-centered* and *input/output-centered* representations of technologies. Suppose one has some metrics in the input/output space, and one is also able to develop, some (albeit inevitable fuzzy) metrics in the high-dimensional "problem-solving space."[12] Granted that, how do the latter map into the former? In particular, were one able to put together all the notional recipes known at a certain time apt to yield a cake (or for that matter a microprocessor or a car) what would the distribution look like in terms of input/output coefficients? In particular, would one find very many recipes which could be ordered in such a way as to be approximately described by a homogeneous function (possibly of degree one)? Indeed, there is nothing a priori in the nature of technological knowledge and in the nature

[12] As we shell briefly survey below, in the literature formal representations of technologies as recipes are quite rare. One of such exception is Auerswald et al. (2000). There the "distance" between any two recipes is the minimum number of operation that must be changed in order to convert one into the other (p. 397). Such a definition is well in tune also with the formalization in Marengo et al. (2000) and Marengo and Dosi (2006).

of recipes and routines which suggests this to be the case (the evidence below will just reinforce the point). In fact, nothing excludes the possibility of recipes that are quite "near" in terms of sequences of procedures which they entail, but quite far in the input/output space. *Vice versa*, it is equally possible to have recipes regarding, say, the production of steel, chemicals, or semiconductors, which might appear at a first look "near" in terms of input intensities but are in fact quite far away from the point of view of underlying knowledge and procedures.

Issues of the same kind regard the relationship between changes in the recipes and routines, on the one hand, and changes in the nature and relative intensities in the use of the various inputs, on the other. Do "small" changes in procedures correspond to "small" changes in input/output relations? And, *vice versa*, do major technological revolutions affecting "the way of doing things" imply also major changes in the proportions in which different artifacts and types of labor enter into the recipes for whatever output? In fact, the existence of possible regularities in the dynamic of procedures, artifact characteristics, and input intensities will be one of the central topics of the next section.[13]

Another implication is that the foregoing view of technologies focused on the procedures involved in, say, designing and manufacturing cars, software, chemical compounds, etc., rather than on the (derived) input/output relations allows a straightforward account for the ample variance in revealed performances across firms which one observes within each industrial sector. Especially if procedures are long, complex and possibly only partly understood by the organizations implementing them, one is likely to expect that (a) each organization knows only one or very few of them, (b) even for apparently similar recipes, any two organizations might master them with very different degrees of effectiveness. Heterogeneity across firms is, thus, the rule, even in presence of identical relative prices: more on all this below.

3. How technologies evolve

As we suggested above, 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 many contributors to the SYS synthesis, cited earlier and also Chandler, 1992; Chandler and Galambos, 1970; Metcalfe, 1994, 1998, 2005b; Mokyr, 1990, 2002; Ziman, 2000.)[14] 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 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 it 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

[13] Germane discussions are in Nelson and Winter (1982), Nelson (1981), Auerswald et al. (2000), Winter (2006a), and Dosi and Grazzi (2006). A somewhat similar problem in biology is the mapping between genotypic and phenotypic structures: see Stadler et al. (2001).

[14] 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 others.

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.

Vincenti (1990) has described the kinds of complex knowledge and technique that modern aeronautical engineers possess, and discusses in detail how these focus and give power to their efforts at design. This body of knowledge and technique enables engineers to roughly analyze the likely plusses and minuses of various design alternatives through analytic methods or simulations, and thus focus their efforts on particular designs and variants. A portion of the body of understanding that guides problem solving and designing by professionals in a technological field comes often from operating experience. At the same time, in the contemporary world, many technologies are associated with specific fields of applied science or engineering. A good deal of the relevant body of understanding is codified in these fields, and serves as the basis for the training of new technologists and applied scientists. And these fields also are fields of research. In modern "high-tech" industries, research in the underlying scientific disciplines is an important source of new understandings and techniques that become part of the kit used by designers (Cohen et al., 2002; Rosenberg and Nelson, 1994; see also below).

Whenever efforts at inventing and designing are oriented by relatively strong professional understanding, *part* of the relevant variation and of 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 tried out there in practice. A good deal of the effort to advance technology proceeds "off-line," as it were. Research and development (R&D) 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 intersectoral 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 proceeds off-line, learning by doing and by using still plays an important role (cf. Freeman, 1994; Rosenberg, 1982, Chapter 6). Pavitt's foregoing point holds throughout past and contemporary technologies: *ex ante* well-codified 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, as Vincenti argues, 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.

We have been sketching so far some quite general characteristics of technological advance that hold across fields and across countries, often driven by diverse behaviors of multiple agents searching and competing with each other. Pushing further, 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*.

3.1. Technological paradigms and technological trajectories

From the earlier discussion it should be clear that 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 Kuhn's (1962) scientific paradigm.[15]

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 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*—that is, 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 aircrafts 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* (see Abernathy and Utterback, 1978; Henderson and Clark, 1990; Rosenbloom and Cusumano, 1987; Suarez and Utterback, 1995; Utterback and Suarez, 1993; 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

[15] Here as well as in Dosi (1982), we use the notion of paradigm in a *microtechnological* sense: for example, 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: for example, 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).

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 are pharmaceutical technologies which *do* involve specific knowledge basis, specific search heuristics, etc.—that is, 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.[16] Whether the establishment of a dominant paradigm entails also the established of a dominant design or not bears a lot of importance also in terms of dynamics of industry structure along the life cycle of the industries to which a particular paradigm is associated. We shall come back to that in Section 4.

Technological paradigms identify the operative constraints on prevailing best practices 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 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 field 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 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.[17] Both properties will turn out to be central when trying to characterize distinct "regimes" of technological and industrial 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 be 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

[16] 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.

[17] 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.

aircrafts, helicopters, various kinds of agricultural equipment, automobiles, semiconductors, and a few other technologies (Dosi, 1984; Gordon and Munson, 1981; Grupp, 1992; Sahal, 1981, 1985; Saviotti, 1996; Saviotti and Trickett, 1992). 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 (Frenken and Leydesdorff, 2000; Frenken et al., 1999; Giuri et al., 2007; Sahal, 1985; 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 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 on computers, from Nordhaus (2007) highlighting also the changing trajectories associated with paradigm changes, and Figure 2 pointing out the long-term trajectory-like patterns in semiconductors and the ways they have

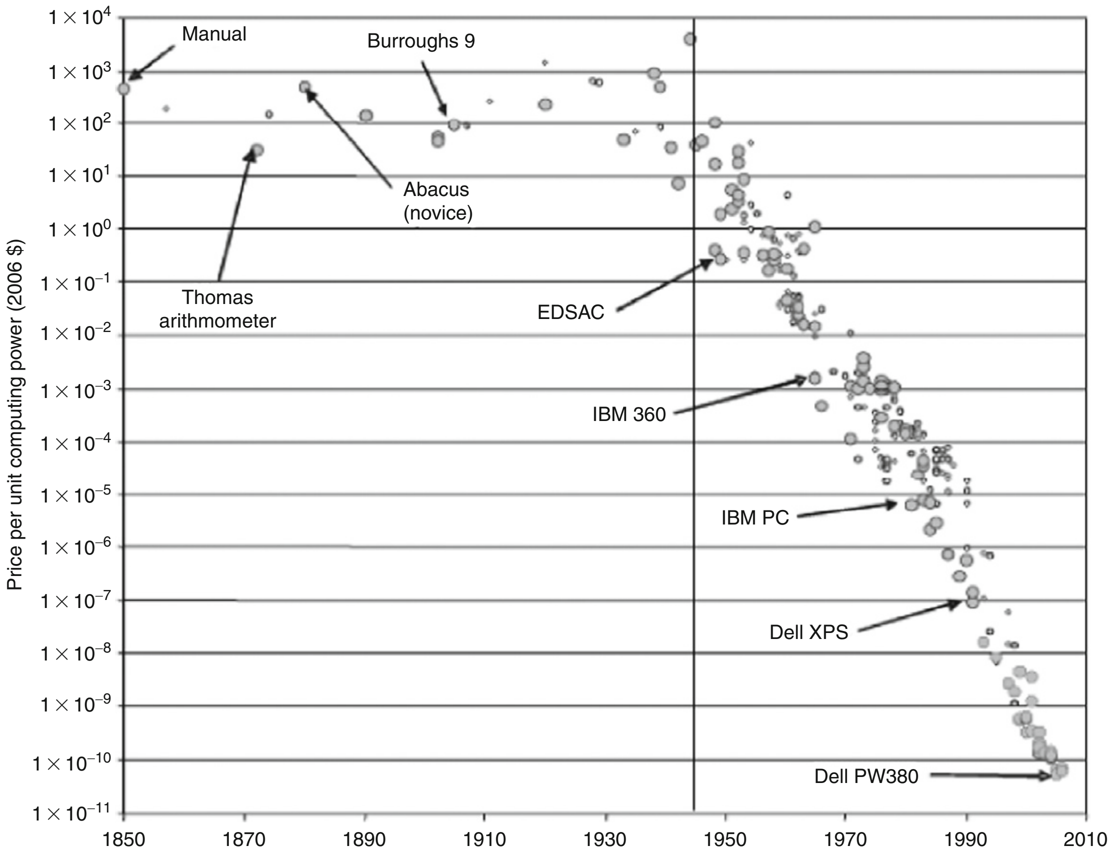

Figure 1. The progress of computing measured in cost per computation per second deflated by the price index for GDP in 2006 prices. Source: Nordhaus (2007).

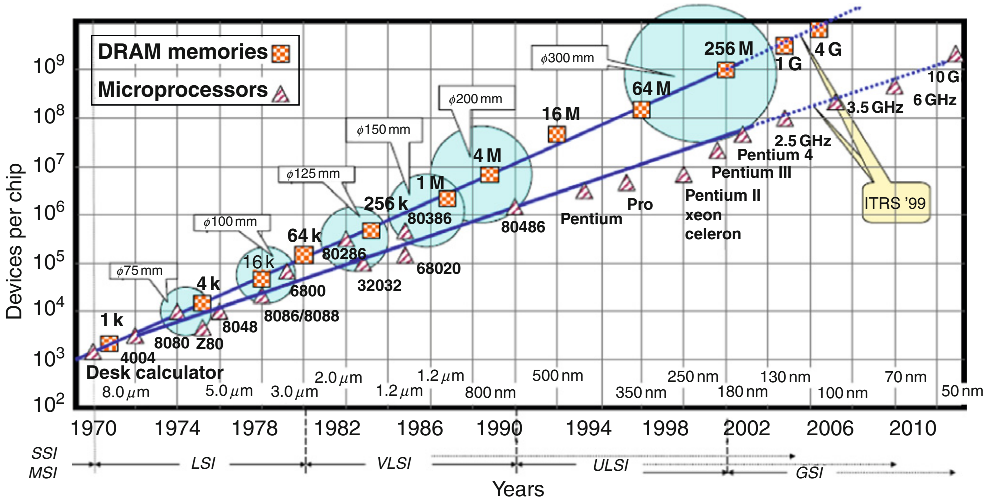

Figure 2. Moore's law and technology scaling. Source: Zheng (2008).

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.)

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 tradeoffs 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"—whatever "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.[18] 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.[19]

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 in different countries, if technologies were perfectly "plastic" and malleable—as standard economic representations are implicitly suggesting—one would tend to observe sorts of "isoquants" with the familiar shape in the space of techniques and of techno-economic characteristics of products. And, over time, if technological recipes—in both 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 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. Of course, one does not always observes clear-cut paradigmatic "revolutions". It is sometimes the case that "normal" advances on established knowledge bases is intertwined with new sources of knowledge. This appears to be the case in electronics-based industrial automation and might apply also to drugs and biotech: cf. Hopkins et al. (2007).

Are there some features which most technological trajectories share?

[18] 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"!

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

A common feature which characterizes trajectories in process technologies and in the related equipment-embodied advances 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.[20] 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*. Chapter 10 is devoted to learning by doing and its different formalizations. Here, 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:

$$p = \alpha X^{\beta}, \tag{1}$$

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)[21] 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, surveys, and discussions see Conoway and Schultz (1959), 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 Chapter 10 in this Handbook. 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 Dosi, 1984; Gordon and Munson, 1981; Jovanovic and Rousseau, 2002; Nordhaus, 2007).[22]

Interestingly, a steady fall in unit labor inputs seems—at least in some circumstances—seems to appear even when holding the equipment constant. It is the so-called "Horndahl effect," named after a Swedish steel mill (Lundberg, 1961), which contributed to inspire Arrow (1962b) on learning by doing.[23] Notice that learning effects are present at the levels of industry, firms and plants, even if rates and intertemporal variabilities are different, 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

[20] For some more detailed discussion, see also Dosi et al. (1990).

[21] Who, somewhat confusingly, calls "performance" the left-hand variable and "prevalence" the right-hand one.

[22] 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.

[23] Strictly speaking, the Horndahl effect showed around 2% per year growth in productivity, and thus, again, linked performance with time and experience rather than accumulated output, but see footnote 22.

of the learning mechanisms underlying the observed performance trajectories and of their variations across different paradigms are indeed important tasks ahead for evolutionary analyses of innovation.[24]

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.

3.2. 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 Mandeville's example of eighteenth-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, 2010; Nelson, 2003; Nelson and Nelson, 2002; Nelson and Wolff, 1997).

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,b, 2004; Nelson, 2004; 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), and Nelson (1981) continues to apply: scientific principles help a lot but are rarely enough. An enlightening case

[24] 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), and Castaldi et al. (2009) among others.

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![25] 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[26] (for a more detailed discussion, see Nelson, 2008a).

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, 1996b; 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 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

[25] In fact, history quite often offers examples of a coevolutionary 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 eighteenth century preceded subsequent advancement in classical thermodynamics and the theory of heat engines, it also holds that earlier attempts 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, 1962–1963) (we thank A. Nuvolari for pointing it out to us).

[26] 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.

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 (see also Breschi et al., 2003). At the opposite extreme, several instances point at patterns of technological change which are anticumulative 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 firm-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.

3.3. Demand and other socioeconomic factors shaping the direction of technological advance

The tendecy 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 firm level 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 (cf. the evidence collected in the still classic Sappho project, comparing innovative successes and failures across otherwise similar firms: cf. Freeman, 1982; similar findings of 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.

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 that their designs have to meet a long list of quite precise requirements which 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 again 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, that is, 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, e.g., irrespectively of the relative price of energy, it is difficult to imagine, given 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 three analytically different ways.[27]

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 (recall also the similar notion of "reverse salients" by Hughes, 1983), from the continental blockade during Napoleonic wars to various instances of technical bottlenecks in mechanical technologies. The mid-nineteenth-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 inducement factors have to do with industrial relations and industrial conflict. As analyzed by Rosenberg (1976), the resistance of nineteenth-century English labor, especially skilled labor, to factory discipline and terms of employment, has acted as a powerful stimulus to technical change. 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 specialized labour. 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).

[27] For important discussions of "inducement effects," see Binswanger and Ruttan (1978) and Ruttan (1997).

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 (United States and world) trajectories in semiconductor devices, or the influence of the characteristics of the US 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; 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[28] and the limits to possible "inducement effects."

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 no *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? More in Dosi, 1982; Freeman, 1982; Mowery and Rosenberg, 1979). The empirical evidence is mixed. Schmookler's empirical research has shown how changes over time in the sales of different kinds of products tend 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,

[28] 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).

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, 1994, p. 480). As emphasized by Freeman himself and by Kline and Rosenberg (1986), the major analytical 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 acknowledgment of a coevolutionary 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—in terms of both 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 they new production techniques or new machines to be sold to a user 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 (a formalization of the process is sketched out below, Section 3.8).

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 of such processes easily allow for endogenous interactions (i.e., "coevolution") between the incentive structure (stemming from relative prices and demand patterns), on the one hand, and learning capabilities, on the other. In this respect, Wright (1997) is an excellent illustration of the point. Even in the case of mineral resources—that is, 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 and more generally, Mowery and Nelson, 1999, Mowery and Rosenberg, 1982, and Nelson, 1999). 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 *ex post* 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, for example, gasoline engines, cheaper steel, electromechanical machine tools, etc. From this point of view, over such longer time-scale 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.

3.4. 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 twentieth 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.[29] In Nelson (2006), David and Hall (2006), and Dosi et al. (2006b), one discusses the dangers coming from the erosion of Open Science institutions. We cannot get into details 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 go 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 fundamental incompatibility—originally pointed out by Marx and Schumpeter—between any sort of zero-profit general equilibrium and any incentive to *endogenous* innovation (i.e., endogenous to the private, "capitalist," sector of the economy).

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

First, how profound is such a tradeoff between monopolistic departures from competitive (zero-profit) conditions and incentives to innovate?[30] 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 the core assumptions 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

[29] On these 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).

[30] Note that the possible "tradeoff" discussed here is distinct from the purported, and somewhat elusive ("Schumpeterian"), tradeoff 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, in Soete (1979) and Cohen and Levin (1989).

industries. The aforementioned 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 Granstrand, 1999, 2005; Jaffe, 2000; Mazzoleni and Nelson, 1998; Dosi et al., 2006c; 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 yesterday's 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 able 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. They show how the IPR regime probably slowed down considerably the subsequent development of automobiles and aircrafts, due to the time and resources consumed by lawsuits against the patents themselves. The current debate on property rights in biotechnology suggests similar problems, whereby granting very broad claims on patents might have a detrimental effect on the rate of technical change, insofar as they preclude the exploration of alternative applications of the patented inventions.

This is particularly the case when inventions concerning fundamental techniques or knowledge are concerned, for example, genes or the Leder and Stewart patent on 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 "oncomouse") but also all the class of products that could be produced through that principle, that is, "all transgenic nonhuman 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 United States—yielded more search/more diverse rates of exploration of "downstream" research paths.[31]

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 Heller and Eisenberg, 1998 and Merges and Nelson, 1994). If past and present components of technological systems are patented by different parties, there can be an *anticommons* problem (the term was coined by Heller and Eisenberg).

[31] It is not possible to discuss here the underlying theoretical debates: let us just mention that models 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).

While in the standard commons problem (such as an open pasture) the lack of proprietary rights is argued to lead to overutilization and depletion of common goods, in instances like biotechnology the risk may be that excessive fragmentation of IPRs among too many owners 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 anticommons 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 (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 with respect to *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 few fields of technology. Pharmaceuticals is an important example. However, a series of studies (Cohen et al., 2002; Levin et al., 1985; Mansfield et al., 1981 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) 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." (p. 33)*

Patenting often appears to be a complementary mechanism for appropriating returns to product innovation, but not the principal one in 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). Teece (1986) and a rich subsequent literature (cf. the Special Issue of *Research Policy*, 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, and 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 the new technology, also by means of complementary assets such as manufacturing capabilities, 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 90% 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, e.g., 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, probably 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.

3.5. Technological advance and the theory of the firm

As mentioned, another chapter of this Handbook is devoted to the management of innovating firms. Here let us just sketch telegraphically some links between the theory of corporate organization and the evolution of technological knowledge and artifacts: related discussions are in Nelson and Winter (1982), Winter (1987, 2006b), Dosi et al. (2000, 2008a), Marengo and Dosi (2006), and Helfat et al. (2007), a few chapters of Fagerberg et al. (2005) and Granstrand (1998).

While in earlier eras much of inventing was done by self-employed individuals, under modern capitalism business firms have become a central locus of efforts to advance technologies. And firms long have been the economic entities that employ most new technologies, produce and market the new products, operate the new production processes. As already mentioned, most modern firm operates in environments that are changing over time in ways that cannot be predicted in any detail. Technological advances are one of the primary forces causing continuing uncertainty, but other causes concern the nature of markets and of competition regardless of whether these are associated with technological advance. That is, to recall, Knightian uncertainty obtains, both of the "substantive" and the "procedural" kinds. In these circumstances there is no way that a truly optimal policy can be even defined (among other things the choice set is not well specified), much less achieved. Rather, firms ought to be seen as "behavioral entities," largely characterized by routinized patterns of action, modified in the longer term by more explicit "strategic" orientations. In turn, as already sketched above, organizational routines and capabilities stemming from ensembles of them represent to a large extent the procedural counterpart of what we have discussed so far largely in terms of knowledge and its dynamics over time. In this respect, possibly one of the most exciting, far from over, intellectual enterprises over the last two decades has involved the interbreeding between the evolutionary research program, largely evolutionary-inspired technological innovation studies, and an emerging competence/capability-based theory of the firm, with complementary roots drawing back to the pioneering organization studies by March, Simon, and colleagues (Augier and March, 2000, 2002; Cyert and March, 1992; March, 1988; March and Simon, 1958; Simon, 1957). Deeply complementary to the analyses of innovative activities focused on dynamics of knowledge, artifact characteristics and input coefficients, organizational analyses have began addressing the behavioral meaning of statements such as "firm X is good at doing Y and Z. . . ." Relatedly, what are the mechanisms that govern how organizational knowledge is acquired, maintained, and sometimes lost?

Organizational knowledge is in fact a fundamental link between the social pool of knowledge, skills, opportunities for discoveries, on the one hand, and the micro efforts aimed at of their *actual* exploration, on the other.

Distinctive organizational capabilities bear their importance also in that they persistently shape the destiny of individual firms—in terms of, for example, profitability, growth, probability of survival. Equally important, their distributions across firms shape the patterns of change of broader aggregates such as particular sectors (see Section 4) and whole countries.

Over time, organizational capabilities change, partly as a result of deliberate search: the ongoing stream of research on *dynamic capabilities* (Helfat et al., 2007; Teece et al., 1997; Winter, 2003) addresses precisely the criteria and processes by which capabilities evolve at least partly steered by the effort of strategic management. But this fact in no way diminishes the significance of the limits on what particular firms are capable of doing at any time, and the constraints on the range of new things that they can learn to do in a reasonable period of time. In fact one often notices the apparent inability of established firms to cope with changes in paradigms associated with the development of alternative technologies based on different design principles and requiring different skills for their mastery and advancement, and the tendency for periods where regimes are changing to be marked by the entry of new firms which may come to dominate the industry in coming years. These limits and constraints on existing firms, and the consequent openness of an industry to entry under conditions when technologies are changing radically are a central aspect of a capability-based theory and also straightforwardly link with the analysis of the drivers of industrial evolution (more in Section 4).

3.6. The dynamic of productive knowledge, and the dynamics of production coefficients

It is a fundamental consequence of the foregoing view of technology and innovation and of the related knowledge-based theory of the firm that firms themselves 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 (i.e. with the same codified elements) they almost certainly will differ in the tacit aspects of those recipes. The ways 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 implications which are indeed 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 a homogeneous good under constant returns to scale with two variable inputs only, x_1 and x_2.[32]

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

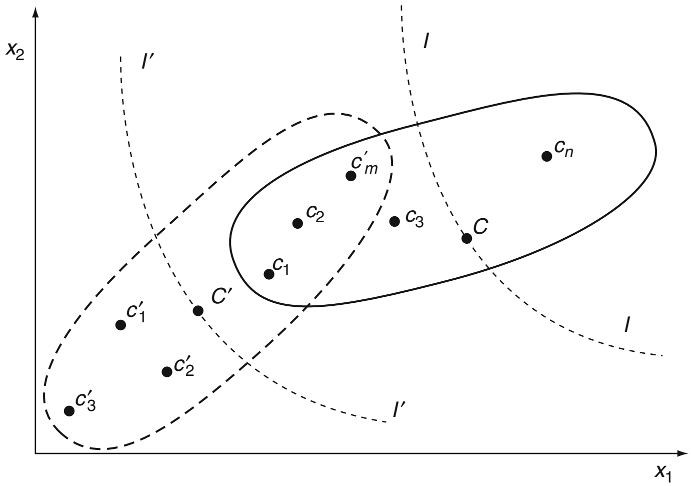

Figure 3. Microheterogeneity and technological trajectories.

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 $c_1,\ldots, c_n$, where $1,\ldots, n$ are the various techniques labeled 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.

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. Baily et al., 1992; Baldwin, 1995; Bartelsman and Doms, 2000; Bottazzi et al., 2007; Dosi, 2007; Jensen and McGuckin, 1997; Nelson, 1981; Power, 1998; Rumelt, 1991; Syverson, 2004).

Typically the support of inter-firm/inter-plant distributions of both labor productivities and "total factor productivity"[33] 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 [labour] productivity ratios within industries are over 4 to 1 and 7 to 1 respectively" (p. 535). Similar interfirm dispersion at three-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 just 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*

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

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 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 form 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), mistake-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 (e.g., in Fig. 3 the standard deviation around the mean value C).

The first question is why doesn't the firm using the nth technique adopt instead technique c_1? 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 $c'_3, \ldots, c'_m$,. 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 three succeeds in leapfrogging and becomes the technological leader while *m* is now the marginal technique). Conversely, does one gain much by adding on the two "isoquants" I and I' passing through the respective means and by calling their shift "technical progress"? In our view, not much: rather it is going to blur the true underlying dynamics just described.

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 microcoefficients 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 (i.e., some loose equivalent of what euphemistically the economic profession calls in international trade the Leontief "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 observe less developed countries which do not only use more labor per unit of output but more capital input as compared to technological leaders (Figure 3 illustrates a similar case: compare, e.g., techniques c_3' and c_1).[34]

3.7. 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 couple of 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 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

[34] 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.

(iii) “Scale-intensive” sectors, wherein the sheer scale of production influence the ability to exploit innovative opportunities partly endogenously generated and partly stemming from science-based inputs.[35]
(iv) “Science-based” industries, whose innovative opportunities coevolve, 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 (1995, 1997), and 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.

Note also that different technological regimes are supported by distinct institutions governing public research and training and, at the market end, by different forms of organization of 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, 2004).

3.8. *Formal models of search and technological evolution*

The dichotomy between knowledge-ridden recipes and routines, on the one hand, and more “black-boxed” input/output representations is also reflected by two quite different styles of modeling, still in search for systematic links with each other.

The newer, and less developed, procedure-centered modeling *genre* builds on the notion that a technology is made of a discrete set of operations or components (Auerswald et al., 2000; Dosi et al., 2003; Levinthal, 1997; Levinthal and Warglien, 1999; Marengo and Dosi, 2006). Whatever name is chosen they stand for physical or cognitive acts eventually leading to the solution of whatever “problem,” being it, for example, the construction of an automobile or the design of a piece of software. Different notional sequences of operations on components are associated with different degrees of efficiency in the solution of such problems (or no solution at all). One way of synthetically capturing these formalizations, represented over a relatively simple topology, is by nesting them over a *fitness landscape*. The notion was originally developed in biology as a way of mapping configurations of possibly interrelated traits into their fitness values (see Kauffman, 1993; Kauffman and Levin, 1987). Within this modeling style central

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

Table 1
Sectoral technological trajectories: Determinants, directions, and measured characteristics

Category of firm	Typical core sectors	Determinants of technological trajectories			Technological trajectories	Measured characteristics			
		Sources of technology	Type of user	Means of appropriation		Source of process technology	Relative balance between product and process innovation	Relative size of innovating firms	Intensity and direction of technological diversification
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Supplier dominated	Agriculture; housing; private services traditional manufacture	Suppliers research extension services; big users	Price sensitive	Nontechnical (e.g., trademarks, marketing, advertising, aesthetic design)	Cost-cutting	Suppliers	Process	Small	Low vertical
Scale intensive	Bulk materials (steel, glass); assembly (consumer durables and 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

Source: Pavitt (1984, p. 12).
PE, Production Engineering Department.

questions regard the characteristics and efficacy of different ways of "decomposing" the overall problem, the implications of different search/adaptation strategies (e.g., whether involving "local" vs. "global" exploration), and the conditions under which "lock-in" into suboptimal outcomes occurs.

A domain of analysis to which such a modeling enterprise seem to straightforwardly apply is the theory of organization and its boundaries, and this is in fact where most of the attention has gone so far (more in Marengo and Dosi, 2006; see the discussion in Dawid, 2006, with reference to a large ensemble of agent-based—ACE—models: more on the latter in Tesfatsion and Judd, 2006). However, to repeat, not much effort has gone so far into the mapping between the recipe dynamics and the input/output dynamics.[36] In a rare exception, Auerswald et al. (2000) assume that the labor requirement associated with each "operation" is a random variable (so that the labor requirement of each recipe is a random field). Indeed, a quite challenging modeling frontier regards the explicit representation of evolving problem-solving procedures, constrained by paradigm-shaped "grammars" and their ensuing dynamics in the more familiar space of input/output coefficients.

As things stand now, even in the evolutionary camp, formal representations of technologies tend to "blackbox" the procedural part. As a result, most of the representations of techniques are in terms of quantities of inputs per units of output, with the output itself being often assumed homogeneous or sometimes defined by specific performance characteristics. Hence, the innovative dynamics is characterized by the evolution of the input vector (and, possibly, the output characteristics vector) over time. At this level of analysis, important modeling questions regard the form, and the support of the probability distribution of "innovative draws" agents may access, whether access is conditioned upon expensive investment ("R&D") and whether innovations are embodied or not in particular pieces of equipment. One feature, however, is common to most evolutionary representations of techniques in that they assume at any given time that firms are characterized by *fixed coefficients* of production (in the jargon they are endowed with Leontief techniques). In our view, this is a quite natural representation of the (degenerate) "production possibility set" firms are able to access in the short term: in fact, agents essentially know how to master the recipe actually in use while it is quite far-fetched to postulate that they have, so to speak, cupboards full of notional recipes which they *could instantaneously adopt* were relative prices different. Rather, any attempt to change technique has to be considered as a time-consuming, innovative effort, most often subject to uncertain outcomes.

Well supported by the microeconomic evidence discussed above, the basic unit of analysis of many evolutionary models are *heterogeneous techniques which at any point in time coexist and compete with each other, and evolve over time according to some search/learning process*. Straightforwardly, each technique can be pictured as a vector $\boldsymbol{x}_{(\cdot,\cdot)}(t)$ specifying, in the simplest case, the quantities of inputs per unit of homogeneous output. Each technique may or may not be labeled also in terms of agents which embody and hence master them. As reviewed in Silverberg and Verspagen (2005a), a family of models sticks to the "technique-as-the-primitive" representation (cf. Conlisk, 1989; Silverberg and Lehnert, 1993, 1994). The postulated "search" under this assumption is blackboxed within some random arrival process, drawing from a time-drifting normal distribution (Conlisk, 1989) or either time invariant or drifting Poisson distributions (Silverberg and Lehnert, 1993, 1994). Think for simplicity of a one-

[36] To our knowledge, the only attempt to link also at a formal level a dynamic in the space of recipes yielding learning-curve-type trajectories in the space input efficiencies is Auerswald et al. (2000) (see also Muth, 1986, albeit for a much more "blackboxed" perspective).

dimensional process, whereby one draws, say, in the space of labor productivities. The process for sound empirical reasons is assumed to be *multiplicative* on the techniques already in use (as witnessed, e.g., by the observed dynamics in labor productivities: cf. Dosi, 2007).

In another style of modeling, the technique is also tagged to specific firms, trying to capture the idiosyncratic features of innovative (and imitative) search. A model to that effect is presented in Iwai (1984a,b), where the distribution of techniques is taken to correspond to a distribution of firms which both innovate and imitate each other (with probabilities that are a function of the frequencies of the particular firms/techniques in the industry).

In quite a few modeling exercises, in tune with Nelson and Winter (1982), firm-level search is represented as a two stages stochastic process. In the first stage firms draw from a Bernoulli process the event "access to innovation" (or to imitation), with a probability dependent on the amount of resources invested in search. A successful draw yields access to a second stochastic process determining the actual "innovation" (or imitation) defined by the input coefficients of a new technique (which in fact might turn out to be inferior to the incumbent one, and in that case the firm sticks to the latter).

The whole family of models typically assumes a process whereby advances are likely to occur in the neighborhood of the techniques already in use within any one firm: this is also a straightforward representation of the *cumulativeness and locality* of technological advances.[37]

It follows also from the foregoing discussion that the ways opportunities are tapped and degrees of success in doing so depend to a good extent upon the capabilities and past achievements of economic agents. So, more technically, think of "opportunities" as some measure on the set of input coefficients which are reachable at time t, with positive probability, conditional on the vector $\boldsymbol{x}_j(t)$ of coefficients that agent j ($j = 1, \ldots, n$) masters at that time. And, straightforwardly, the transition probabilities can be seen as capturing both paradigm-specific opportunities and capabilities, specific to each j for any given search effort.[38] Differing opportunities can be straightforwardly captured by different width of the support of the probability distribution of possible draws, as well as by the shape of the distribution itself.[39]

It is also relatively easy to formalize the "inducement mechanisms" discussed in Section 3.3. Effects on the *direction of search* formally imply that market shocks induce different partitions of the notional search space attainable at t, and focus search in those regions where one is more likely to find, say, savings on the inputs which are perceived as scarce and more expensive. Note that, for example, part of the (highly convincing) interpretation of inducements to mechanization in the American nineteenth-century economy suggested by David (1975) can be rephrased in this way.[40]

[37] Related formalizations of "local" technical learning are in Atkinson and Stiglitz (1969) and Antonelli (1995).

[38] This is to make things simple: in more complicated but more realistic accounts, allowing for imitation, transition probabilities of each j should depend also on the states achieved by all other agents and some metrics on their distances: see, for example, Chiaromonte and Dosi (1993), Dosi et al. (1994a), and Fagiolo and Dosi (2003).

[39] For example, in Dosi et al. (2006a), one assumes a β-distribution which, depending on the parameterization, may attribute the major mass to "bad draws" (in the case of scarce opportunities) and *vice versa*. The opportunities actually tapped depend crucially also on the agents' ability to explore and exploit them. In Nelson (1982), we sketch a model with a two-stage stochastic process ("study and test" and next "design/blueprint drawing") wherein agents' knowledge influences the "quality" of the choice set of new techniques—in terms of expected cost for achieving an advance of a given magnitude or expected magnitude of advances for a given R&D investment.

[40] Without any analytical loss, except the dubious commitments to rational choice with reference to a mysterious "innovation possibility frontier."

As already mentioned, relative prices may induce changes in the *revealed* directions of technological change even when the micro directions of search remain invariant.

Let us illustrate it by recalling the very basics of the Markov model of factor substitution from Nelson and Winter (1982, pp. 175–192).

It has been mentioned earlier that "innovative opportunities," when talking about process innovations, can be represented as the (bounded) set of states in the space of inputs (per unit of output) attainable starting from an arbitrary technique in use at time t. Suppose that search is a random process invariant in t (this implies that one excludes both decreasing returns to innovative efforts and those inducement effects upon search rules, discussed earlier). As already sketched in Section 3.3 when a new technique is drawn, it is compared with the one currently in use, given the prevailing input prices, and the minimum cost one is obviously chosen. The sequence of factor ratios displayed by a firm can be described by a Markov process characterized by the transition probability matrix $\boldsymbol{F} = [f_{ik}]$, where f_{ik} is the probability that state i follows state k.[41] Note that the transition matrix is time invariant but actual transition probabilities depend on relative input prices. This is because of the "comparison check": holding constant the initial technique and the one drawn, whether the latter will be adopted or not might depend on relative prices,[42] and such a choice will set different initial conditions for the next draw, etc. The intuition on dynamic-choice-of-technique inducement suggests that if the relative price of some input increases, the transition probabilities, loosely speaking of "getting away" from the techniques which intensively use that input will also increase. And in fact, Nelson and Winter (1982, pp. 180–192) establish the result, in a two-input case, that, with the appropriate ordering in terms of relative input intensities, the transition matrix $\hat{\boldsymbol{F}}$ (based on the new relative prices) stochastically dominates the "old" one, $\boldsymbol{F}$. It is an appealing result, resting so far on many formal qualifications, but certainly worth further exploration.[43] The bottom line is the following. Even if opportunities do not change and agents do not change their search rules, it is enough that relative prices enter into the criteria of choice between what has been found by search and what is already in use, to determine—in probability—"induced" changes in the patterns of factor use, at the level of individual firms and whole industries.[44]

[41] Nelson and Winter (1982), quite in tune with the general idea that there are "paradigm-based" constraints to the scope of factor substitution, assume that factor ratios can take only N possible values; thus, $i, k = 1, \ldots, N$.

[42] It obviously does not whenever the newly discovered technique is more efficient in terms of every input—a case which evolutionary interpretations easily allow.

[43] Among other points, the clarity of representation in terms of a time-invariant finite-state Markov process has its inevitable downside in that—taking seriously the question of "what happens as time goes to infinity?"—all persistent states return infinitely often in the limit (see also below on path dependency). However, it should not be formally impossible to make transition probabilities phase-space dependent, thus giving also more persistence to the weight of past "inducements." However, more down to the earth, does the fact that in the mathematical limit, say, Honduras will interchange with Sweden an infinite number of times weakens the (indeed, formally, transient-bound) proposition that both Sweden and Honduras are likely to display path-dependent technical coefficients over any reasonable, finite, window of observation?

[44] We do not dare extend this conjecture to whole economies, since not much has been done toward the exploration of multi-sectoral systems, linked by input–output relations, checking also the empirical plausibility of phenomena like reswitching of techniques, etc.—which appeared prominently in the theoretical debates in the 1970s and disappeared by magic later on. A few evolutionary formalizations are multisectoral, including Verspagen (1993) and some include also an admittedly rudimentary input/output structure such as Chiaromonte and Dosi (1993), Fagiolo and Dosi (2003), and Dosi et al. (2008b), but, to our knowledge none has addressed the dynamics of technique in a multisector "general disequilibrium" framework.

Evolutionary formalizations of search, innovation and imitation abhor any assumption of "rational technological expectations," and thus deny the possibility, in the actual world and in theory, of deriving the amount of resources devoted to search from unbiased expectations about probabilities of innovation/imitation the future returns from them. Rather, the somewhat extreme opposite assumption is generally made: propensity to invest in R&D are time-invariant behavioral routines possibly changed only if performances fell below a certain "satisfying" threshold (with few exceptions: see Silverberg and Verspagen, 1996 for a model with adaptive variations of such propensities to invest in search; Kwasnicki and Kwasnicka, 1992; Yildizoglu, 2002 for a model wherein R&D rules evolve stochastically by means of a genetic algorithm-based search).

Clearly firm-specific dynamics of innovation nurture a persistent heterogeneity across firms in terms of production efficiencies (and, too rarely in the models but most often in reality, product characteristics) curbed only to a partial extent by the processes of imitation. In turn, as we shall discuss in Section 4, such interfirm differences underlie different competitive abilities and contribution to shape the evolution of industrial structures.

3.9. Invention, innovation, and diffusion

Innovation diffusion is the subject of Chapter 17, and we refer to it for a more detailed survey of the evidence.[45] However, as that chapter is explicitly confined to equilibrium analyses of such an evidence, let us offer some basic elements of distinct interpretations more in tune with the evolutionary view outlined so far.

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 three major stylized facts already highlighted by early classic analyses including Mansfield (1961), Griliches (1957), Nabseth and Ray (1974), and Rosenberg (1972, 1976) are, *first* that diffusion is a time-consuming process, *second* that the speed varies widely across technologies and across countries, *third*, that 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

[45] See also Hall (2005), Nakicenovic and Gruebler (1991), Geroski (2000) and Stoneman (2007), and the discussions from an evolutionary angle in Metcalfe (1988, 2005a).

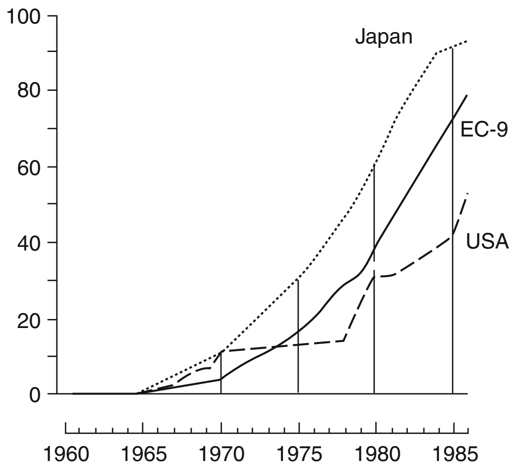

Figure 4. The diffusion of continuous casting of steel, as a percentage of total crude steel production. Source: Ray (1989, p. 4).

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 acknowledgment 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.

On the supply side, heterogeneity is amply endogenous to the dynamics of learning, innovation, imitation, and selection among producers (see the next section): product characteristics and their prices change and with that also the market shares and the very identity of producers themselves.[46]

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 as 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; Gary et al., 2008). Conversely, the frequent requirements of organizational changes associated with the adoption of innovations, especially when the latter are producer

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

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 convincingly 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.

How does one formally represent such dynamics? In a nutshell, full-fledged evolutionary models of innovation, imitation, and selection basically entail diffusion dynamics as a corollary of the whole process (Silverberg et al., 1988 is an early example). Interestingly, evolutionary models are capable of generating the major "stylized facts" of diffusion dynamics recalled earlier as *emergent properties* of the evolutionary process whereby the system collectively "self-organize" around the use of a new technology. However, an interesting family of "reduced-form" models compresses the interfirm competition dynamics while offering a succinct account of diffusion nested into heterogeneous populations, and driven by dynamic increasing returns, network effects, and endogenous preferences. A powerful and versatile formal instrument are *generalized Pólya urns* (cf. Arthur et al., 1987; Dosi and Kaniovski, 1994; Bassanini and Dosi, 2001, 2006). Let us just recall here that such formal machinery is well apt to account for (a) the influences of stochastic events along the evolutionary dynamics upon the long-term outcomes (and thus the related path dependency of technology selection); (b) the widespread importance of dynamic increasing returns (possibly intertwined with forms of decreasing returns within "badly behaved" dynamics: cf. Dosi and Kaniovski, 1994); and (c) the possibility that technological evolution "gets it wrong" (in the sense of convergence to the dominance of a technology which is "inferior" to other ones available in some form from the start, which however the collective dynamics of adoption did not reinforce: see below).

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 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. To recall, the QWERTY keyboard became dominant, as David argued, through path dependent externalities in production and use, notwithstanding its intrinsic inferiority to other configurations.

3.10. 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. Since other chapters of this Handbook are devoted to these two topics, we need not address the details of such phenomena. However, again, let us flag their role in technological evolution. (We shall come back to some of the issues below when addressing industrial evolution.)

Let us consider 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, and 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. Arthur, 1988, 1989; David, 1985, 1988, 2001b; Dosi and Kaniowski, 1994; and a few contributions to Antonelli et al., 2006). 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—for example, 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 that 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 advantage. 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. David's (1985) story 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 AC over DC 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 optimizing virtues of Divine Providence).

4. Schumpeterian competition and industrial dynamics

The evidence discussed in the previous section highlights both the general characteristics that technological knowledge displays and at the same time the widespread diversity in the mode and efficacy by which individual firms access and exploit such knowledge even when undertaking very similar activities and operating in the same lines of business.

Idiosyncratic capabilities and, dynamically, idiosyncratic patterns of learning by individual firms are the general rule. In turn, such persistently heterogeneous firms are nested in competitive environments which shape their individual economic fate and collectively the evolution of the forms of industrial organization. In the following, we shall first offer an overview of some broad features of such competitive environments. Next, we shall consider at greater detail a few properties of the processes of industrial evolution, trying to distinguish those elements which are common to all industries and others which are regime-specific. Finally, we shall discuss the modeling efforts which try to interpret the patterns of industrial evolution.

Differences in products, and in processes of production—and as a consequence in costs and prices—are central features of the competitive process in which firms are involved at multiple levels. Let us call *Schumpeterian competition* the process through which heterogeneous firms compete on the basis of the products and services they offer and get selected, with some firms growing, some declining, some going out of business, and some new ones always entering on the belief that they can be successful in this competition. Such processes of competition and selection are continuously fuelled by the activities of innovation, adaptation, and imitation by incumbent firms and by entrants. Such processes involve both selection *across firms*, and learning and selection among techniques, organizational practices, and product attributes *within* the firms themselves.

In all that user selection of particular technological variants over others, together with firms' selection in financial markets, are central drivers of competition, industrial demographics, and changing industry structures. It is important to consider both users and suppliers. It is reasonable to start from the observation that the production and adoption of "superior" consumption goods, capital goods, and intermediate inputs often underlies the competitive advantage of particular firms. And, indeed, a major analytical question bears on the precise drivers and mechanisms of the competition process. Another one regards how long "competitive advantages," of whatever kind, last. In industries where a company which introduces a very attractive innovation is able to prevent rapid imitation by competitors, and also is able to expand its own market share rapidly, the result may be a highly concentrated industry. This certainly has been the result in some well-known cases, for example, IBM's long domination of the mainframe computer industry, and Intel's continuing domination of the market for microprocessors. However, in many other instances successful innovators have not been able to develop and hold on to a dominant market position, in the face of continuing efforts at innovation by their competitors. Joseph Schumpeter employed the term "creative destruction" to refer both to the nature of technological advance, and to what often happens to leading firms in industries where technological advance is rapid and incumbents are unable to seize novel opportunities. In fact, significant changes in industrial structure as a result of innovation are more likely when the success of a particular new product or process is associated with the ascendancy of new technological paradigms. Successful innovations in these cases are associated with different design concepts, or different ways of doing things, than what it replaced. Continued viability of firms in this area of activity then may require learning to work effectively with the (partly) new knowledge bases and new organizational routines. In such a context, an industry structure that had been stable for a considerable period of time may be ripe for the success of new entrants.

If we step back from the details of particular industry patterns, there are a few general properties that stand out from industry studies. *First*, as Schumpeter, and Marx before him, argued long ago, competition in industries where innovation is central has little to do with the idea that such process generates results that are economically "efficient" in the standard static sense of that concept in economics. What is driving the process is the striving by some firms to get an economic advantage over their competitors. As discussed in Section 3, both the cross section and the time profiles of modern industrial sectors inevitably show considerable variation across firms in measures of economic efficiency and in profitability: in short, industries are characterized by considerable and persistent "inefficiency" in the standard allocative sense of that term. *Second*, in industries marked by continuing innovation, competitive conditions may be fragile. This applies particularly to the cases whereby firms who have been successful innovators are able to hold off imitation or other effective competitive responses, and their profitability enables them to stretch their advantage further. *Third*, this notwithstanding, while the evolutionary notion of "competition" differs from competition of the economic textbooks in fundamental respects, it does serve a related function. To the extent competition is preserved, a significant share of the benefits of technological progress go to the customers/users of the technology. And on the supply side, over industrial evolution, competition tends to roughly keep prices moving in line with costs (including R&D costs).

This is the bird eye interpretation of innovation-driven competition and the ensuing industrial evolution. How well does it hold against the evidence? Are there some finer regularities in such processes? What are the distinct characteristics of firms and their distribution which systematically persist over time, if any? How do such characteristics within the population of competing firms affect their relative evolutionary success? And, moreover, among the foregoing properties and relation between them which ones are invariant across industries, and, conversely, which ones depend on the technological and market characteristics of particular sectors?

Let us begin with the evidence concerning some features of the *dynamics* in (i) *industrial structures* and *firms characteristics*, broadly understood to cover variables such as size, productivity, innovativeness, and their intraindustry distributions; (ii) *performances*—including individual profitabilities, growth profiles, and survival probabilities, together, again, with their aggregate distributions; and (iii) their mapping into *regimes of learning*—for example, modes of innovative search, etc. (cf. Section 3.7).[47]

4.1. Microeconomic heterogeneity: Size, to begin with

We have repeatedly emphasized it already: firms persistently differ over all dimensions one is able to detect.

A first, extremely robust, "stylized fact" regards the quite wide variability in firm sizes. More precisely, one observes—throughout industrial history and across all countries—right-skewed distributions of firm sizes: within a large literature see Steindl (1965), Hart and Prais (1956), Ijiri and Simon (1977), Hall (1987), Bottazzi et al. (2007), Lotti et al. (2003), Bottazzi and Secchi (2005), and Dosi (2007).

Irrespectively of the precise form of the density function, the intuitive message is the coexistence of many relatively small firms with quite a few large and very large ones—indeed in a number much higher than the one would predict on the ground of any Gaussian shape. In turn, all this militates against any naive notion of some "optimal size" around which empirical distributions should be expected to fluctuate. Notice that, as a consequence, also any theory of production centered around invariant U-shaped cost curves, familiar in microeconomic theory, looses a lot of plausibility: were they the

[47] See more on all this in Dosi et al. (1995, 1997) and Dosi (2007), where one can find also a more detailed discussion of the literature.

rule, one ought to reasonably expect also a tendency to converge to the corresponding technologically optimal equilibrium size. On the contrary, plausible candidates to the representation of the empirical size distributions are the log-normal, Pareto, and Yule ones. Certainly, the full account of the distributions suffers from serious problems in offering also an exhaustive coverage for the smallest firms. Recent attempts to do that, such as Axtell (2001) on the population of US firms, lend support to a *power law* distribution linking firm size probability densities with the size ranking of firms themselves.

All this primarily concerns *aggregate manufacturing* firm size distributions. Are these properties robust to disaggregation? Size differences are. However an increasing body of finer sectoral data suggest that in fact invariances in the distributions are not. Corroborating a conjecture put forward in Dosi et al. (1995) and further explored in Marsili (2001), aggregate "well-behaved" Pareto-type distributions may well be a puzzling outcome of sheer aggregation among diverse manufacturing sectors, characterized by diverse regimes of technological learning and market interactions, which do not display Paretian distributions. While some sectors present distributions rather similar to the aggregate ones, others are almost log-normal and yet others are bimodal or even multimodal. (More evidence is summarized in Dosi, 2007). Together, admittedly circumstantial evidence hints at a plausible oligopolistic core versus fringe firms separation in several sectors—indirectly supported by the mentioned bimodality of size distributions.[48]

Finally, note that even relatively stable industrial structures—as measured in terms of stability of size distributions—hide a much more turbulent microeconomics. Incumbents change their relative share and ranking[49] with a lot of "churning" of new firms: roughly half disappear before they get to the age of 5,[50] but a subset of the survivors grows to significant share of most industries, and is also an important carrier of innovation and productivity growth.[51]

Come as it may, industrial structures—in this case proxied by size distributions—are the outcomes of the growth dynamics undergone by every entity in the industrial population (jointly, of course, with birth and death processes). What about such growth processes?

4.2. *Corporate growth rates and corporate profitabilities*

There are many studies that have explored empirically the extent to which Gibrat's law, which proposes that firm growth rates are multiplicative and statistically independent of size, is a good first approximation of actual industrial dynamics. Lotti et al. (2003) provides a rich review. The evidence suggests that:

(i) Most often, smaller firms that survive over the period under analysis on average grow faster than larger firms. However, most studies do not count firms in existence at the start of the period that disappear somewhere over the period, and many small firms are young firms that generally have high mortality rates.

[48] Indeed, an important research task ahead concerns the transition probabilities between "core" and "fringe."

[49] Cf. with Louça and Mendonça (2002) on long-term patterns in the upper tail of the size distributions over the whole industrial sector. However, within-industry rankings seem to be rather inertial: on German evidence Cantner and Krüger (2004). See also the comments in Dosi et al. (2008c).

[50] For comparative evidence of the OECD countries, compare with Bartelsman et al. (2005).

[51] Converging pieces of evidence are in Audretsch (1997), Baldwin and Gu (2006), and Foster et al. (2008).

(ii) No strikingly robust relationship appears between size and average rates of growth (cf. Bottazzi and Secchi, 2006; Bottazzi et al., 2003; Coad, 2008; Hall, 1987; Kumar, 1985; Mansfield, 1962; Sutton, 1997 among others). The relationship between size and growth is modulated by the age of firms themselves—with age, broadly speaking, exerting *negative* effects of growth rates, but *positive* effects on survival probabilities, at least after some post-infancy threshold (cf. Evans, 1987).[52]

Such pieces of evidence are easily consistent with evolutionary theories of industrial change. Indeed an evolutionary interpretation would be rather at odds with a notion of convergence to some invariant "optimal" size, with decreasing returns above it. Conversely, it is rather agnostic on the precise specification of *non-decreasing* returns. In particular, it does not have any difficulty in accepting a world characterized by *roughly constant returns to scale*, jointly with drivers of firm growth uncorrelated on average with size itself. Conversely, precious clues on the basic characteristics of the processes of market competition and corporate growth are offered by the statistical properties of the "error term." Note in this respect that the absence of any structure in the growth processes would be very damaging indeed to evolutionary theories of industrial change. In fact, if one were to find corroboration to any "strong Gibrat" hypothesis according to which growth would be driven by a multiple, small "atomless" uncorrelated shocks, this would come as bad news to evolutionary interpretations whose basic building blocks—to recall—comprise the twin notions of (i) persistent heterogeneity among agents and (ii) systematic processes of competitive selection among them. What properties in fact do the statistics on firm growth display?

One of the most important pieces of evidence able to throw some light on the underlying drivers of corporate growth regards the distribution of growth rates themselves. The evidence suggests an extremely robust stylized fact: growth rates display distributions which are *at least exponential (Laplace) or even fatter in their tails*.[53] This property holds across (i) levels of aggregation, (ii) countries, (iii) different measures of size (e.g., sales, employees, value added, assets), even if (iv) one observes some (moderate) variations across sectors with respect to the distribution parameters. Such statistical properties are indeed good news for evolutionary interpretations. The generalized presence of fat tails in the distribution implies much more structure in the growth dynamics than generally assumed. More specifically, ubiquitous fat tails are a sign of some underlying correlating mechanism which one would rule out if growth events were normally distributed, small, and independent. In Bottazzi et al. (2003) and Dosi (2007), one conjectures that such mechanisms are likely to be of two types. First, the very process of competition induces correlation. Market shares must obviously add up to one: someone's gain is someone else's loss. Second, in an evolutionary world one should indeed expect "lumpy" growth events (of both positive and negative sign) such as the introduction of new products, the construction/closure of plants, entry to and exit from particular markets.[54]

Together with corporate growth, profitability is another crucial measure of revealed corporate performances. Concerning the variable, there is indeed a robust literature on the *persistent profitability*

[52] Moreover, the statistical relationships between size and growth rates appear to be influenced by the stage of development of particular industries along their life cycles: cf. Geroski and Mazzucato (2002).

[53] See Stanley et al. (1996) and Bottazzi and Secchi (2003) on US data, Bottazzi et al. (2001a) on the international pharmaceutical industry, Bottazzi et al. (2002, 2003) on the Italian industry, and the discussion in Dosi (2007).

[54] A suggestive attempt to model increasing-return dynamics yielding the observed fat-tailed distribution is in Bottazzi and Secchi (2005).

differences across firms: see, among others, Mueller (1986, 1990), Cubbin and Geroski (1987), Geroski and Jacquemin (1988), Geroski (1998), Goddard and Wilson (1999), Cefis (2003a), Gschwandtner (2004), and Dosi (2007). Moreover, the autocorrelation over time in profit margins is extremely high in all manufacturing sectors, with just a relatively mild tendency to mean reversion, while, interestingly, the rates of change in profit margins display distributions which are again fat-tailed (at least exponential, or even fatter-tailed). That is, we find again here the mark of powerful underlying correlation mechanisms which tend to induce “coarse-grained” shocks upon profitabilities.

Indeed, the bottom line is that core indicators of corporate performances such as growth and profitability confirm the already familiar widespread multifaceted *heterogeneity* across firms notwithstanding the competition process. Given all that, a natural question concerns the roots of such heterogeneity itself.

4.3. Behind heterogeneous performances: Innovation and production efficiency

Straightforward candidates for the explanation of the differences in corporate performances are in fact (i) differences in the ability to innovate and/or adopt innovation developed elsewhere regarding product characteristics and production processes, (ii) different production efficiencies, (iii) different organizational arrangements, and (iv) different propensities to invest and grow conditional on the foregoing set of variables. Plausibly the former three ensembles of variables may be expected to be related with each other (the behavioral aspects are a distinct matter). For example, technological innovations typically involve also changes in the organization of production; different ways of searching for innovations imply distinct organizational arrangements regarding the relationships among different corporate tasks (e.g., R&D, production, sales, etc.). And, intuitively, technological and organizational innovations ultimately shape the degrees of efficiency in which inputs happens to generate outputs.

What is the evidence concerning the patterns of technological innovation, on the one hand, and production efficiencies on the other? (We are forced to neglect here the role of organizational variables. In fact, *organizational capabilities* are intimately linked with the very process of technological innovation and with production efficiencies: cf. the insightful evidence in Brynjolfsson and Hitt, 2000.)

We have discussed at length in Section 3.7 the evidence on asymmetries in production efficiencies—no matter how measured, for example, in terms of labor productivities or TFPs: widespread and persistent asymmetries are the general rule.

Together, the literature on the economics of innovation surveyed in Section 3 primarily from the angle of knowledge dynamics, indeed suggests widespread differences across firms in their ability to innovate:

(i) Innovative capabilities appear to be highly asymmetric, with a rather small number of firms in each sector responsible for a good deal of innovatios even among highly developed countries.
(ii) Somewhat similar considerations apply to the *adoption* of innovations, in the form of new production inputs, machinery, etc. (see Section 3.9 on “diffusion”) revealing asymmetric capabilities of learning and “creative adaptation.”
(iii) Differential degrees of innovativeness are generally persistent over time and often reveal a small “core” of systematic innovators (cf. Bottazzi et al., 2001a; Cefis, 2003b; Cefis and Orsenigo, 2001; Malerba and Orsenigo, 1996a among others).

(iv) Relatedly, while the arrivals of major innovations are rare events, they are not independently distributed across firms. Rather, recent evidence suggests that they tend to arrive in firm-specific "packets" of different sizes.[55]

In fact, all the evidence on wide asymmetries in the abilities to innovate and imitate is consistent with the interpretation of the patterns of knowledge accumulation put forward in Section 3. And so is the evidence on micro correlations of innovative events, well in tune with an evolutionary notion of few, high-capability, persistent innovators.

On a much larger scale, the persistent asymmetries across countries, even within the same lines of business, cry out in favor of profound heterogeneities in learning and searching capabilities.[56]

4.4. Corporate capabilities, competition, and industrial change

Differences in innovative abilities and efficiencies (together with differences in organizational setups and behaviors) ought to make up the distinct corporate "identities" which in turn should somehow influence those corporate performances discussed above.

But do they? How? And how are these relations influenced by behavioral (partly "strategic") considerations on the side of individual firms?

Let us consider first the impact of different degrees of innovativeness and different efficiencies upon profitability, growth, and survival probabilities.

In several studies, firms that are identified as innovators tend to be more profitable than other firms: see Geroski et al. (1993), Cefis (2003a), Cefis and Ciccarelli (2005), Roberts (1999), and Dosi (2007) among others. Production efficiency also shows a systematic positive influence upon profitability (cf. Bottazzi et al., 2009; Dosi, 2007).

The impact upon growth is much less clear cut. Certainly, there are some serious questions about how both superior innovative performance and superior production efficiency are identified and measured.[57] Even if the measurements are taken at face value, the impact of both measured innovativeness and production efficiency upon growth performances appear to be quite uncertain. Mainly North American evidence, mostly at *plant* level, does suggest that increasing output shares in high-productivity plants and decreasing shares of output in low-productivity ones are important drivers in the growth of sectoral productivities, even if the process of displacement of lower efficiency plants is rather slow (cf. the evidence discussed in Ahn, 2001; Baily et al., 1992; Baldwin, 1995; Baldwin and Gu, 2006). *Firm-level* data are less straightforward. For example, Italian and French data (cf. Bottazzi et al., 2009; Dosi, 2007)

[55] On the statistical properties of the discrete innovations, in general, cf. Silverberg (2003) showing a secular drifting Poisson-type process. However, at a much finer level of observation the firm-specific patterns of innovation do not happen to be Poisson-distributed. Rather, as one shows in Bottazzi et al. (2001a) in the case of the pharmaceutical industry, few firms "draw" relatively large "packets" of innovations well described by Bose–Einstein (rather than Poisson) statistics.

[56] Much more on that in Dosi et al. (1990), Verspagen (1993), Fagerberg (1994), Nelson (1996), and Cimoli et al. (2009).

[57] An important caveat here is that there might be an intrinsic sample selection bias in the data in favor of *successful* innovations: firms that try to innovate and do badly are not adequately counted as innovative firms. Another caveat, is that generally "efficiency" is measured, due to data availability, in terms of deflated value added or deflated sales, folding together price and volume levels, and dynamics. A rare exception is Foster et al. (2008) who are able to draw upon microdata separating the two at microlevel.

show a weak or nonexistent relationship between relative (labor) productivities and growth: more efficient firms do *not* grow more. Moreover even when some positive relation between efficiency and growth appears, this is almost exclusively due to the impact of few *outliers* (the very best and the very worst).

Concerning the impact of innovation the evidence from some industry-specific data sets such as the international pharmaceutical industry shows that more innovative firms do *not* grow more (Bottazzi et al., 2001a; for some qualifications of the statement still on the drugs industry cf. Demirel and Mazzucato, 2008; and concerning a few high-tech sectors cf. Coad and Rao, 2008). Rather the industry constantly displays the coexistence of heterogeneous types of firms (e.g., innovators vs. imitators). There is a sort of a puzzle here awaiting further research in that such statistical evidence appears to be somewhat at odds with more qualitative reconstructions of industrial evolution whereby technological advances appear to be at the centre of competitive advantages and ultimately the drive toward corporate leadership: cf. among others Dosi (1984) on semiconductors and Murmann (2003) on chemicals.

In complementary efforts, a growing number of scholars has indeed began doing precisely what we could call *evolutionary accounting* (even if most do not call it that way; however for an early example of the *genre*, cf. Nelson and Winter, 1982). The fundamental evolutionary idea is that distributions (including, of course, their means, which end up in sectoral and macro statistics!) change as a result of (i) learning by incumbent entities, (ii) differential growth (i.e., a form of selection) of incumbent entities themselves, (iii) death (indeed, a different and more radical form of selection), and (iv) entry of new entities. Favored by the growing availability of micro longitudinal panel data, an emerging line of research (see Baily et al., 1996; Baldwin and Gu, 2006; Bottazzi et al., 2009; Brown et al., 2006; Foster et al., 2001 among others, and the discussion in Bartelsman and Doms, 2000) investigates the properties of decompositions of whatever mean sectoral performance variable, typically productivity of some kind, of the following form, or variations thereof:

$$\begin{aligned}\Delta\Pi_t = {} & \textstyle\sum_i s_i(t-1)\Delta\Pi_i(t) + \sum_i \Pi_i(t-1)\Delta s_i(t) \\ & + \textstyle\sum_e s_e(t)\Pi_e(t) + \sum_f s_f(t-1)\Pi_f(t-1) \\ & \quad + \text{some interaction terms,}\end{aligned} \tag{2}$$

where Π are the productivities (or, for that matter, some other performance variables), s are the shares[58] of each firm in the industry total, while i is an index over incumbents, e over entrants, and f over exiting entities.

The first term stands for the contribution of firm-specific changes holding shares constant (sometimes called the *within* component), the second one captures the effects of the changes in the shares themselves, holding initial firm productivity levels constant (also known as the *between* component) and the last two take up the effect of entry and exit, respectively.

Of course, there is a considerable variation in the evidence depending on countries, industries and methods of analysis. However, some patterns emerge. *First*, the *within* component generally is significantly larger than the *between* one: putting it another way improvement of productivity by existing firms *dominates selection* across firms as a mode of industry advancement—at least concerning productivity (both labor and TPF). This emerges both from the foregoing "evolutionary accounting" exercises and from estimates of the relationship between efficiency and subsequent growth, allowing for firm fixed effects. And, it holds in both the short and the medium term. So, for example, in the analyses of Bottazzi et al. (2009) on Italy and France, firm-specific factors generally account for almost an order of

[58] Shares in terms of what is a delicate issue: in terms of output? Value added? Or, conversely, employment? Relocation of resources and output across firms involves both changes in inputs and market shares.

magnitude more than "selection" of the variance in firm growth rates. *Second*, relative efficiencies do influence survival probabilities, and it may well turn out that selective mechanisms across the population of firms operate much more effectively in the medium–long term at this level rather than in terms of varying shares over the total industry output.

We have focused so far upon the linkages between admittedly rough proxies for innovativeness and productivity, on the one hand, and growth and survival, on the other. What about the relationships between profitability and the latter two variables? The evidence we are familiar with strikingly shows little or no link between profitability and firm growth of incumbents (cf. again Bottazzi et al., 2009 on Italian and French longitudinal data). However, other pieces of evidence suggest also systematic effects of profitability upon survival probabilities (cf. the discussion in Bartelsman and Doms, 2000; Foster et al., 2008).

The implications of all these empirical regularities are far-reaching.

Certainly, the recurrent evidence at all levels of observation of *interfirm heterogeneity* and its persistence over time is well in tune with an evolutionary notion of idiosyncratic learning, innovation (or lack of it) and adaptation. Heterogeneous firms compete with each other and, given (possibly firm-specific or location-specific) input and output prices, obtain different returns. Putting it in a different language, they obtain different "quasi rents" or, conversely, losses above/below the notional "pure competition" profit rates. Many firms enter, a roughly equivalent number of firms exits. In all that, the evidence increasingly reveals a rich structure in the processes of learning, competition and growth. As mentioned, various mechanisms of correlation—together with the "sunkness" and indivisibilities of many technological events and investment decisions—yield a rather structured process of change in most variable of interest—for example, size, productivity, profitability—also revealed by the "fat-tailedness" of the respective growth rates. At the same time, market selection among firms—the other central mechanism at work together with firm-specific learning in evolutionary interpretations of economic change- does not seem to be particularly powerful, at least on the yearly or multiyearly timescale at which statistics are reported (while the available time series are not generally long enough to precisely assess what happens in the long run, say, decades). Conversely, diverse degrees of efficiencies and innovativeness seem to yield primarily relatively persistent profitability differentials. That is, contemporary markets do not appear to be too effective selectors delivering rewards and punishments in terms of relative sizes or shares—no matter how measured—according to differential efficiencies. Moreover, the absence of any strong relationship between profitability and growth militates against the "naively Schumpeterian" (or for that matter "classic") notion that profits feed growth (by plausibly feeding investments). Selection among different variants of a technology, different vintages of equipment, different lines of production does occur and is a major driver of industrial dynamics. However, it seems to occur to a good extent *within* firms, driven by the implementation of "better" processes of production and the abandonment of older less productive ones.

Finally, the same evidence appears to run against the conjecture, put forward in the 1960s and 1970s by the "managerial" theories of the firm on a tradeoff between profitability and growth with "managerialized" firms trying to maximize growth subject to a minimum profit constraint.[59]

[59] In fact, the absence of such a tradeoff had been already noted by Barna (1962). Note also that this proposition is orthogonal to the finding that current growth appears to be correlated with *future* long-term profitability (cf. Geroski et al., 1997).

In turn, the (still tentative) observation that market selection that winnows directly on firms may play less of a role than that assumed in many models of evolutionary inspiration (see below) demands further advances in the understanding of how markets work (or do not), and of the structure of demand (broadly in the perspective of this work, cf. Nelson, 2008b, and Aversi et al., 1999). Here note the following. *First*, one measures "efficiency"—supposedly a driver of differential selection—very imperfectly: we have already mentioned, as emphasized by Foster et al. (2008), that one ought to disentangle the price component of "value added" (and thus the "price effect" upon competitiveness) from "physical efficiency" to which productivity strictly speaking refers. This applies to homogeneous products and even more so when products differ in their characteristics and performances: as this is often the case in modern industries, one ought to explicitly account for the impact of the latter upon competitiveness and revealed selection processes. *Second*, but relatedly, the notion of sharp boundaries between industries and generalized competition within them is too heroic to hold. It is more fruitful in many industries to think of different submarket of different sizes as the locus of competition (cf. Sutton, 1998). The characteristics and size of such submarkets offer also different constraints and opportunities for corporate growth. Ferrari and Fiat operate in different submarkets, face different growth opportunities and do not compete with each other. However, the example is interesting also in another respect: Fiat can "grow," as it actually happened, by acquiring Ferrari. *Third*, a growing microevidence highlights the intertwining between technological and organizational factors as determinants of Schumpeterian competition: Bresnahan et al. (2008) illustrate the point in the case of IBM and Microsoft facing the introduction of the PC and the browser, respectively. Both firms, the work shows, faced organizational diseconomies of scope precisely in the corporate activities where they were stronger. *Fourth*, in any case, the links between efficiency and innovation, on the one hand, and corporate growth, on the other, are mediated by large degrees of *behavioral freedom*, in terms, for example, of propensities to invest, export, expand abroad; pricing strategies; patterns of diversification; etc.

4.5. Industry-specific dynamics and industry life cycles

So far, we have discussed some properties of industrial evolution which appear to hold broadly across all industrial sectors. Conversely, are there sectoral specificities in the patterns of industrial evolution? And do they map into those different technological and production regimes discussed above? Moreover, different sectors happen to be at different stages of their life cycles. How does that influence the characteristics of the processes of industrial evolution?

In fact, significant industry-specific differences emerge from the data. The finding that variables like capital intensity, advertising intensity, R&D intensity—along with structural measures like concentration and performance measures like profitability—differ widely across sectors is at the very origin of the birth of industrial economics as a discipline. Longitudinal microdata add further evidence. So for example, Jensen and McGuckin (1997) observe that industry-specific effects also significantly influence firms' heterogeneity, even if most of the observed variance in plants and firms characteristics is *within* industries.[60] Thus, it

[60] Other studies (e.g., Geroski and Jacquemin, 1988; Mueller, 1990) showed that the persistence of profit also appears to depend on industry-specific characteristics as well as on firm-specific ones. In particular, industry-specific features such as the intensity of advertising and of R&D appear to be highly correlated with the persistence of higher than average profits.

should not come as too big a surprise that phenomena like entry, exit, and survival, persistence in firms attributes and performances, innovative activities and firms' growth also exhibit significant interindustry variability. Audretsch (1997) reports on the relationships between entry, exit, and survival entrants on the one hand, and industry characteristics like the rate of innovation and capital intensity on the other. This evidence suggests, in particular, that survival is easier in those industries in which small firms are important sources of innovation, and that new surviving firms tend to grow faster in innovative industries and as a function of the gap between minimum efficient scale of output and actual firm size. At the same time, however, the likelihood of survival decreases as a function of that gap. The same happens in terms of innovation rates.

Can one move a step further and link at least some characteristics of evolutionary patterns with the underlying technological regimes? It is a conjecture put forward in Winter (1984) and Dosi et al. (1995), explored in both circumstances via simulation models, which the empirical evidence begins to corroborate (Marsili, 2001; Marsili and Verspagen, 2002), even if probably more disaggregate classification of the regimes themselves are needed beyond the "Schumpeter Mark I" versus "Schumpeter Mark II" distinction. Together *market regimes* variables have to be introduced (Marsili and Verspagen, 2002).

Do different industrial regimes correspond also to different innovation strategies of business firms? The issue is still largely underexplored; however, Srholec and Verspagen (2008) suggest that within a sector, strategic heterogeneity dominates upon sectoral effects: indeed, a challenging puzzle crossing over economics and strategic management.

Thus far our discussion has been concerned with differences that exist across industries at any time. Now we shift our attention to changes that occur over time within an industry.

No matter the technological regime in which they are embedded, individual industries evolve since their emergence all the way to their maturity, and frequently decline.

Klepper (1997) offers a broad fresco of many *industry life cycle dynamics*:

> *"Three stages of evolution are distinguished. In the initial exploratory or embryonic stage, market volume is low, uncertainty is high, the products design is primitive, and unspecialized machinery is used to manufacture the product. Many firms enter and competition based on product innovation is intense. In the second, intermediate or growth stage, output growth is high, the design of the product begins to stabilize, product innovation declines, and the production process becomes more refined as specialized machinery is substituted for labour. Entry slows and a shakeout of producers occurs. Stage three, the mature stage, corresponds to a mature market. Output growth slows, entry declines further, market shares stabilize, innovation are less significant, and management, marketing and manufacturing techniques become more refined. Evidence on first mover advantages [. . .] and the link between market shares and profitability [. . .] suggests that the firms that ultimately capture the greater share of the market and earn the greatest returns on investment tend to be those that enter earliest." (Klepper, 1997, p. 148)*

Moreover, the surviving and often dominant firms tend to be those characterized by distinct innovative capabilities (Klepper and Simons, 2005; Bergek et al., 2008; Cantner et al., 2009) which often were there at the start of the firms themselves.

There are now a large number of studies exploring the explanatory power of technology/product cycle theory in a wide range of industries. For many industries major parts of the story hold up pretty well.[61] Figure 5A–C regarding cars, tires, and TVs is a good illustration. However, there is a range of industries where economies of scale in production never become so great, or the advantages of learning by doing so significant, that only large firms can survive, and entry is blocked. Many "supplier-dominated" sectors (cf. Pavitt's taxonomy above) such as textiles and clothing are good examples. In other cases, while the large economies of scale predicted by product life cycle (PLC) theory in fact have emerged, the nature of the demand for a product class is sufficiently varied so that a single dominant design cannot emerge and take a large share of the overall market. As surveyed in detail by Klepper (1997), alternatives to the canonic PLC template include *first*, industries wherein the dominant trend is toward "Smithian" specialization across components along the overall production chain. *Second*, and relatedly, the requirements by end users may well be sufficiently diverse to define technologically diverse market niches. When, together, knowledge maintains a significant tacit cumulative and niche-specific component, such submarkets are likely to be supplied by different firms throughout the history of the industry. As we discuss in Dosi et al. (2008c) this is the case of most producer good industries including machine tools and instruments and several "complex product systems" (cf. Figure 5D for an illustration concerning lasers; the case of jet engines is discussed in Bonaccorsi and Giuri, 2000).

Equally interesting deviations from (or complications of) the technology cycle theory are industries where, while something like a product cycle dynamic seems to hold in particular eras, from time to time significantly new technologies arise, which upset the old order, and start off a new product cycle. Striking cases include the dramatic changes in aircraft systems technology, and together the identity of the dominant firms, set in train when the turbojet engine became preferred to the older gasoline reciprocating engines; the change in the dominant players in electronic circuitry when transistors and later integrated circuits replaced vacuum tubes; the rise of biotechnology as a vehicle for drug discovery and design. Note that these are essentially cases associated, at least partly, to *paradigm discontinuities*. In these and other cases when a radically new technology has replaced an older mature one, as we have noted, old dominant firms often have difficulty in making the adjustments. In such circumstances, technological change has been what Tushman and Anderson (1986) have called "competence destroying." The industry may experience a renewal of energy and progress, but often under the drive of a new set of firms.

4.6. Models of industrial dynamics

How does one formally represent the processes of industrial evolution? Evolutionary models of industrial dynamics—and economic change more generally—rest on the representation of multiple "boundedly rational" heterogeneous agents interacting with each other (Nelson and Winter, 1982; Bottazzi et al., 2001b; Dosi et al., 1994a, 1995, 2006a; Iwai, 1984a,b; Malerba et al., 1999, 2007, 2008; Silverberg and Lehnert, 1993; Silverberg and Verspagen, 1996; Winter, 1984; Winter et al., 2003; see also the early insights in Winter, 1971).

[61] In such industries, the transition between the initial to the "mature" phase appears to be associated also with different degrees of instability of market shares (cf. Mazzucato, 2002 on the PC industry) and departures from Gibrat-type properties of growth (which seems to be higher in the post-shakeout phase: cf. Geroski and Mazzucato, 2002).

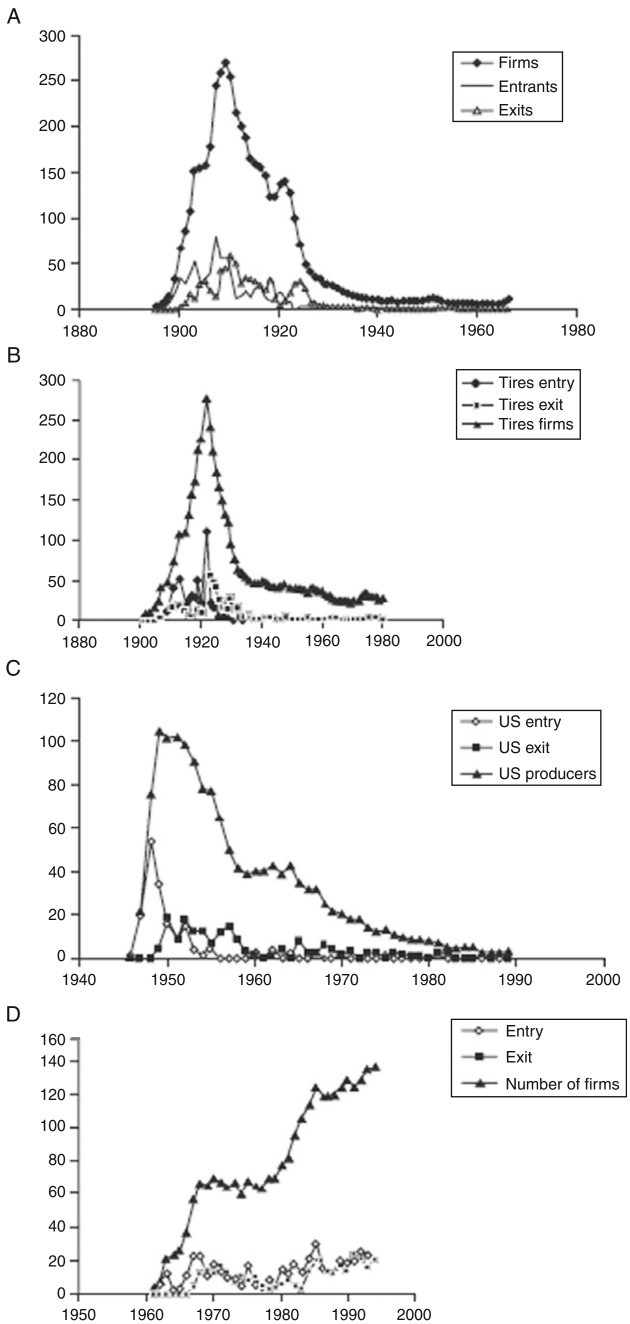

Figure 5. Entry, exit, and number of (A) automobile producers, 1985–1996; (B) tire producers, 1901–1980; (C) television producers, 1946–1989; and (D) laser producers, 1961–1994. Source: Arora et al. (2006).

"Bounded rationality" also takes the form of limited understanding by the agents of the causal structure of the environment in which they are embedded and a limited ability to think through future contingencies, while behavioral patterns are often described in terms of relatively invariant routines. On the other hand, in this approach agents are capable of learning and thus improve their performance over time by changing their technologies and organizational practices.[62]

The symmetric complement of the assumptions on what agents know, learn, and do concerns how markets (and other interaction environments) operate. Observed industrial dynamics are obviously the joint outcome of both. But it makes a lot of difference (except for some rather peculiar circumstances), in terms of the properties of the dynamics themselves, whether and to what extent individual entities can figure out, so to speak "in their heads," *ex ante*, what is going to happen to them, at least in probability, because they also know (and possibly collectively share) a common "model" of their environment and shape their decision accordingly. In that respect, evolutionary models are far from that extreme view whereby everyone knows *ex ante* everything that is relevant to know—about, for example, technologies, distribution of "talents" or other causes of heterogeneity across the population of agents, strategies, etc.—and thus markets operate essentially as collective arrangements setting incentive-compatible schemes. In that, since agents "work it out" beforehand, not much happens through the markets themselves—the consistency of individual plans being guaranteed by the (certainly "hyper-rational") assumptions on micro knowledge.[63] Evolutionary interpretations are nearer the opposite interpretation whereby agents hold quite different views on what is going to happen to them (or to the same effect that they hold a rather wild distribution of beliefs largely uncorrelated with what economists call the "fundamentals") and, together, operate a diverse array of both physical and "social" technologies. This applies notwithstanding the fact that firms in any one industry share a similar body of technological knowledge, that is the same paradigm.[64] Under these circumstances, markets operate first of all as selection devices, determining, *ex post*, profitabilities, survival probabilities, and rates of growth.[65] Short of any belief in full micro rationality and collective equilibrium, the challenge for evolutionary models is to understand how joint processes of micro learning and collective selection yield the observed dynamic patterns. And, indeed, this is a central task for evolutionary interpretations.[66] There, as already mentioned, the commitment to individual rationality is much lower and, symmetrically, the explanatory burden placed upon some combination of idiosyncratic innovative learning and

[62] Broadly defined "bounded rationality" applies—even more so—in models of organizational ecologies (for surveys and discussions, see Carroll, 1997; Carroll and Hannan, 2000) whereby firms carry with them their idiosyncratic features at birth.

[63] Of course, this view implies also that empirical observations—such as those presented above—should in principle be interpreted as sequences of equilibrium outcomes, nested into collectively consistent, highly sophisticated, plans of intertemporally maximizing agents (and this is indeed the spirit by which Hopenhein, 1992; Lucas, 1978, e.g., try to account for the evidence on skewed distributions of firms' sizes, positive rates of entry and exit, etc.).

[64] And in fact it happens that the effective entry of technologies based on a new paradigm often requires also the entry of new firms (a formalization of this idea is in Malerba et al., 2007).

[65] Interpretations based on "pure selection" and "pure *ex ante* rationality" happen to be equivalent whenever the underlying equilibria coincide, and, together, each empirical observation might be understood to be a rather close approximation to the "limit" (in a mathematical sense) of some adjustment process operating at a timescale of order of magnitude faster than that at which empirical observations themselves are collected. Frankly, we find this possibility rather awkward, at best, as a general interpretative framework.

[66] Including Nelson and Winter (1982), Winter (1984), Silverberg et al. (1988), Dosi et al. (1995), Bottazzi et al. (2001b, 2007), Winter et al. (2000, 2003), and Silverberg and Verspagen (1996).

market selection is correspondingly higher. An explicit market dynamics is assumed. Innovation is the main engine of dynamics and evolution. As biologists would say, the "evolutionary landscape" upon which evolution occurs is not fixed, but is continuously deformed by the endogenous learning activities of agents. Relatedly, one ought to interpret the aggregate regularities that are observed in the data as emerging from disequilibrium interactions among heterogeneous agents on the basis of some well-specified dynamic process.

We have reviewed above (Section 3.8) a few evolutionary approaches to modeling the *learning* part of the dynamics, that is the formal representation of stochastic innovation and imitation by individual firms. Conversely, the *selection* part of the process is basically captured by different instantiations of some *replication dynamics*—in a closer or looser analogy with the biological counterpart.[67] The bottom line is a relation between some corporate characters—that is, technological, organizational, or behavioral traits—which the particular interactive environment "favors," on the one hand, and the rate of variation of the frequencies in the *carriers* of such characters in the relevant populations on the other (more in Andersen, 2004; Metcalfe, 1998, 2005b; Silverberg, 1988; Silverberg and Verspagen, 2005b). A basic formulation in discrete time is

$$\Delta s_i = f(E_i(t) - \bar{E}(t))s_i(t), \tag{3}$$

where $s_i(t)$ is the market share of firm i at t, $E_i(t)$ is a sort of (blackboxed) measure of its "competitiveness" in turn determining the relative "fitness" (with $\bar{E}(t) = \sum_i E_i(t)s_i(t)$). Of course, *first*, the $E_i(\cdot)$ may well change over time, and indeed the learning dynamics is precisely about such changes. Moreover, *second*, E_i is most likely a vector capturing multiple corporate features influencing the revealed "competitiveness" of each firm. *Third*, the $f(\cdot,\cdot,\cdot)$ function is most likely nonlinear (hence a further reason for a "rugged selection landscape"). *Fourth*, needless to say, one may add varying degrees of stochastic noise to the selection process, apart from the inherent stochasticity of firm-specific processes of change. In the basic linear case with fixed micro characteristics it is possible to derive analytically also some important properties of the dynamics of *industrial means* as a function of the *variances* across the micro $E_i(\cdot)$ variables.[68]

Many evolutionary models explicitly represent the selection process entailed by market interactions via variants of a replicator equation: see, for example, Silverberg et al. (1988), Verspagen (1993), and Dosi et al. (1995, 2006). In other models the "replication process" is implicit into the rates of expansion/contraction of heterogeneous firms as a result of their differential efficiencies. Nelson and Winter (1982) is an exemplar of this modeling approach. Different production efficiencies imply different firm-specific unit costs. The latter (possibly modulated by some behavioral rules governing output) determine different unit profit margins for each firm. If there is some monotonic relation between profit margins and investments in future production capacity, higher efficiency yields higher investment which entails higher relative shares into the $(t + 1)$ overall output.

[67] The original biological formulation comes from Fisher (1930).

[68] More in Metcalfe (2005b). Incidentally note that the whole field of *evolutionary games*, which we cannot discuss at any detail here, fundamentally studies the process of (deterministic or, more often, stochastic) adaptation/selection across a population of *given* traits/trait-carrying agents by analyzing its asymptotic properties (a little more discussion congenial to our argument here is in Dosi and Winter, 2002).

A replication process similar in spirit involves equipment-embodied technological advances and rates of adoption of particular vintages proportional to their profitabilities: see for example, Soete and Turner (1984) analyzing technological diffusion and Silverberg and Lehnert (1993) for a model addressing the microeconomics of long-term growth.

For the most part the models considered above are highly abstract and general. The recent modeling of Malerba et al. (1999, 2007, 2008) is guided by another theoretical strategy: that of trying to explain particular patterns of evolution observed in certain industries.[69]

One has only begun to systematically link evolutionary models with the "stylized facts" of industrial dynamics discussed earlier, and, together of macrodynamics and growth. Here the big challenge regards the ability of the models of generating—and in that sense "explaining"—rich ensembles of observed empirical regularities, both those that are generic, holding across sectors, countries and phases of the industry life cycles, and those that are regime-specific. Indeed, what the analytical perspective has achieved so far is highly encouraging: it has contributed, in our view, important insights on the nature and drivers of industrial dynamics, highlighting also the ways different patterns of learning and market selection influence variables such as the degrees of industrial concentration, turbulence in market shares, the dynamics of asymmetries across firm in production efficiency, and firm mortality.[70]

One major field of exploration has been indeed the mapping between regimes of learning and the ensuing industrial dynamics—from Nelson and Winter (1982) on the "Schumpeterian tradeoffs"; to Winter (1984) on the properties of different innovative regimes; to Dosi et al. (1995), Marsili (2001), Winter et al. (2000, 2003), and Bottazzi et al. (2001b). More precisely, Dosi et al. (1995) and Marsili (2001) study the ways differences in the processes by which innovative opportunities are tapped (e.g., by entrants vs. incumbents, with or without cumulative learning) affect the evolution of industry structures, the degrees of turbulence of the latter, and the statistical properties of corporate growth. Conversely, Bottazzi et al. (2001b) and Winter et al. (2000, 2003) focus on the properties of the "churning" process characterizing industrial evolution, and on the ensuing dynamics in costs and prices.

Another major area of analysis has focused upon more aggregate statistical phenomena. After all, one of the major questions addressed in Nelson and Winter (1982) and earlier Nelson (1968) was indeed whether the model was able to *generate* as an *emergent property* (at the time this was not the language but in fact the meaning) macro-time series analogous to those analyzed by Robert Solow in his pioneering growth accounting and modeling efforts. And the answer was gloriously positive. A good deal of work has gone on in the area. In fact all evolutionary models naturally generate innovation-driven endogenous growth resting on underlying industrial dynamics of the type discussed above. Some models of evolutionary growth have studied the features of the micro dynamics and the interaction

[69] The authors call their style of modeling "history friendly." As the name suggests, it is meant to be much nearer to the phenomenology of particular industry dynamics, their technological and market characteristics, and the actual chronology of events (e.g., the introduction of the PC in the history of computers or that of integrated circuits in the history of semiconductors) and symmetrically try to account for relatively detailed features of the actual evolution of particular industries.

[70] Incidentally note in this respect that evolutionary modes have abundantly vindicated the proposition that market structures, rather than being a determinant of innovative patterns, are—at least in a first instance—the outcome of innovation-driven industrial evolution.

patterns underlying the long-term properties of growth (cf. Chiaromonte and Dosi, 1993; Silverberg and Lehnert, 1994; Silverberg and Verspagen, 1994). Other has focused upon the convergence/divergence dynamics among trading economies (cf. Dosi et al., 1994b; Verspagen, 1993 among others). More recently, one has begun to explore the properties of growth dynamics jointly with an ensemble of "cyclical" macro properties (e.g., fluctuations in macro demand, employment rates, investment, etc.) grounded upon the same evolutionary industrial foundations (cf. Dosi et al., 2006a, 2008b and Dawid, 2006 which offers a broad survey of the general family of agent-based models).

More generally, the reader is invited to refer to Dosi et al. (1988), Dopfer (2005), Malerba and Brusoni (2007), and Hanusch and Pyka (2007) to grasp the progress that has been made since Nelson and Winter (1982), both empirically and theoretically, toward a full fledged evolutionary theory of economic change, and also the gaps that are still there. As we see it, there is a very promising and very challenging future ahead for evolutionary/agent-based formalizations. The ambition, not out of reach, is to offer a relatively unified interpretation of a large ensemble of phenomena at different level of aggregation—ranging from the "industrial stylized facts" discussed above to phenomena concerning the properties of growth and fluctuations (and crises). Concerning the theoretical tools, if we were to pick just one major challenge to *formal* evolutionary modeling, we would name the following.

More work certainly is needed on selection processes and dynamics. A major step forward in this respect would involve a detailed analysis of *how markets work*. Surprisingly enough, we still have very few empirical works of the kind pioneered by Kirman and colleagues (Delli Gatti et al., 2001; Kirman, 2001; Weisbuch et al., 2000), studying the institutional architectures, the actual mechanisms of exchange, and the ensuing dynamics of prices and quantities. And, symmetrically, we have still very few models—most likely of the "agent-based" kind (cf. again the critical review in Dawid, 2006)—exploring the same phenomena from the side of the theory. Needless to say, the analysis of how markets work is crucial to understand what are the main dimensions of the "selection" landscape and how market selection operates.

As we have noted, to date most formal evolutionary modeling has presumed that a large share of "selection" occurs through the selection on firms—and through that on the technologies and practices of which firms are carriers (i.e., the equivalent of their "genotypes"), while the empirical evidence suggests that this is not the main part of the selection story. At least over the short and medium run a good deal of selection of techniques and practices goes on *within* firms. Moreover, the generality of evolutionary models so far has assumed some monotonicity in the relations between "fundamental" determinants of competitiveness/revealed "fitness," and subsequent relative growth.[71] However, as we have seen above, the evidence on these selective processes suggests that selection forces, on practices as well as on firms, are weaker than those theorized. In turn, these persistent asymmetries may well be the consequence of various forms of market "imperfections"—including informational ones—which, together with endemic "satisficing" behaviors, allow firms characterized by diverse degrees of efficiency and product qualities to coexist without too much selective pressure. On the modeling side such evidence entails two complementary challenges. *First*, one ought to pay more attention to the workings of diffusion processes into the evolutionary dynamics (one of the few incumbent examples is Silverberg et al., 1988). *Second*, the models ought to be able to account for evolution occurring over "fitness landscapes" which for a good portion are roughly *flat*.

[71] Note that the same considerations apply, *just much more so*, to "equilibrium evolutionary dynamics" such as those in Jovanovic (1982) and Ericson and Pakes (1995).

5. Innovation, industrial evolution, and economic growth: Some conclusions

In this chapter, we have led the reader from the investigation of the nature and dynamics of *technological knowledge* all the way through the analysis of how technological (and organizational) innovation and imitation drive the evolution of industries. The understanding of the *structure* of technological knowledge and its diversity across different technological paradigms, together with the understanding of the ways such knowledge is generated, augmented, and diffused—we have argued—are fundamental also for the understanding of the rates and directions of innovative activities, well beyond the incentive economic agents face.

Different abilities to innovate and imitate are central aspects and drivers of industrial evolution, shaping the patterns of growth, decline and exit over populations of competing firms, as well as the opportunities of entry of new firms. In this chapter, we have discussed such dynamics as evolutionary processes driven by the twin forces of (often mistake-ridden) idiosyncratic learning by persistently heterogeneous firms, on the one hand, and (imperfect) market selection delivering prizes and penalties—in terms of profits, possibilities of growth, and survival probabilities—across such heterogeneous corporate populations, on the other. In that, we argued, firm-specific learning processes appear to be relatively more powerful than between-firms selection dynamics.

The learning going on in an economy has a collective as well as an individual element. While their capabilities and actions remain far from identical, firms in the same industry often learn similar things about how to operate the technological developments that are emerging. And firms learn from each other, sometimes as a result of deliberate communication, sometimes because at least a portion of what is going on in individual firms becomes public knowledge. As we stressed, the broad elements of technological paradigms are common property for technical people in a field. As a consequence, even while selection on firms often is relatively weak, there generally is significant selection on new technological variants that are being introduced to the field, with advances that tend to get into the general practice, although, as the diffusion studies we described earlier attest, the process may take considerable time.

We have also here the basic ingredients of an evolutionary interpretation of economic growth and development. Such an evolutionary account, which we cannot discuss in detail here, would highlight the significant differences in the rates of progress at any time across different technologies and industries, which we alluded to in our earlier discussion. There is a developing body of research and writing that aims to explain such differences (see, e.g., Nelson, 2003, 2008a). As mentioned earlier, an important underlying variable seems to be the strength of the scientific fields that illuminate the technologies used in an area of practice. However, there clearly are a number of factors at work. And as we have noted, while there are exceptions, progress within a field of technology tends to become more narrowly focused and to slow down as the technology matures. While repressed in neoclassical growth theory, the process of economic growth as we have historically experienced it has been driven by the continuing introduction of new products and new technologies, and the continuing shifting of resources from older industries where the rate of advance had slowed down to emerging new industries. The continuing growth of output per worker and per-capita incomes that industrialized economies have experienced would not have been possible without this kind of an evolutionary process.[72]

A full evolutionary account of economic growth would also take into account that the historical time path of growth tends to be punctuated by "eras" characterized by the development and diffusion of specific constellations of "general-purpose" technologies (Bresnahan and Trajtenberg, 1995; Rosenberg and Trajtenberg, 2004), that is broad techno-economic paradigms in the sense of Perez (1985), Freeman and Perez (1988), and Freeman and Louça (2001). During a particular economic era, much of the economic growth is accounted for by innovation and productivity growth in the industries that produce the goods that directly incorporate the driving technological paradigms and also in the downstream industries that are able to use these goods as inputs (historically, this was the case of steam power, later electricity and the internal combustion engine, and today it is the case of ICT technologies).[73]

Evolutionary processes of economic growth are embedded in a rich structure of institutions. There is now an extensive empirical literature concerned with the institutions of what have been called innovation systems (see Freeman, 1993; Freeman and Louça, 2001; Lundvall, 1992; Nelson, 1993). That literature has been concerned with matters like cooperative arrangements among firms, the role of universities in technological progress and modes of university–industry interaction in different industries, the variety of government programs supporting technological advance, and other supporting institutions. Others relevant institutions pertain to the "political economy" of socio-economic arrangements governing how firms are organized and managed, labor markets, finance/industry relations, corporate laws, etc. In fact, a general conjecture here is that economic growth is driven by the coevolution of technologies and institutions (Freeman, 2008; Nelson, 2008c; Boyer and Saillard, 2002; Hodgson, 1999).

Detailed analysis of macroeconomic growth as an innovation-driven evolutionary process, however, is beyond the scope of this chapter. Consider the foregoing discussion as a sketch of its underlying building blocks.

[72] In fact, an important link between the evolution of individual sectors and aggregate dynamics rests upon their changing shares of output and employment—intertwined as they are by evolving input/output profiles and final demand patterns. The analysis of the dynamics of sectoral structures has been pioneered long ago by Kuznets (1972), Burns (1934), Mitchell (1925), and Svennilson (1954) among others, but unfortunately largely neglected in more recent times. However, those structural changes—which have been formally discussed by Pasinetti (1981) and more recently Saviotti and Pyka (2008a,b)—are a crucial link between changes in individual industries, the primary locus of innovation, diffusion and competition, and broader aggregates. (See also Metcalfe et al., 2005). In this respect, incidentally note how the bad habit common to a good deal of the contemporary economic discipline to compress interagent intrasectoral relations as well as intersectoral ones into some dynamics driven by a purported "representative agent," has obfuscated both the characteristics of industrial dynamics, and also the drivers and properties of macro growth and fluctuations.

[73] Granted that, the relationship between techno-economic paradigms (and even more so individual general-purpose technologies thereof), on the one hand, and growth patterns, on the other, continues to be a challenging area of investigation. In this respect note that chronology of diffusion of general-purpose innovations is far from smooth (a good illustration in the case of the steam engine is in Nuvolari and Verspagen, 2009). Moreover, the application of the same technology in different sectors is characterized by quite uneven rates of technical change (a point already noted by Pavitt, 1986, concerning the impact of microelectronic technologies). Broad discussions on such a relationship are in von Tunzelmann (1995), Freeman and Louça (2001), and Perez (2002). A critical discussion of the very notion of "General Purpose Technologies" is in Field (2008).

Acknowledgments

Comments by Marianna Epicoco, Bronwyn Hall, Stan Metcalfe, Alessandro Nuvolari, Carlota Perez, Nate Rosenberg, and Sid Winter on previous drafts or direct antecedents have helped a lot to shape the work. Mario Cimoli, Marco Grazzi, Luigi Orsenigo and Mauro Sylos Labini coauthored earlier papers upon which we draw. Giorgia Barboni and Matteo Barigozzi have been competent research assistants. Last but not least, we thank Laura Ferrari who helped the work along with utmost competence and endless patience. Support to one of us (G. Dosi) has been granted by the European Community's 6th FP (Contract CIT3-CT-2005-513396), Project: DIME—Dynamics of Institutions and Markets in Europe 7th FP (FP7/2007-2013) under Socioeconomic Sciences and Humanities, grant agreement no. 217466, and MIUR, PROT 2007HA3S72_003, PRIN 2007.

References

Abernathy, W.J., Utterback, J. (1978). "Patterns of innovation in industry". Technology Review 80 (7), 40–47.

Abramovitz, M. (1993). "The search for the sources of growth: Areas of ignorance, old and new". Journal of Economic History 53 (2), 217–243.

Ahn, S. (2001). Firm dynamics and productivity growth: A review of micro evidence from OECD countries. Working Paper No. 297, OECD, Paris.

Akerlof, G.A. (1984). An Economic Theorist's Book of Tales. Cambridge University Press, Cambridge.

Alchian, A. (1963). "Reliability of progress curves in airframe production". Econometrica 31 (4), 679–693.

Allen, R.C. (1983). "Collective invention". Journal of Economic Behavior & Organization 4, 1–24.

Andersen, E.S. (2004). "Population thinking, Price's equation and the analysis of economic evolution". Evolutionary and Institutional Economics Review 1, 127–148.

Antonelli, C. (1995). The Economics of Localized Technological Change and Industrial Dynamics. Springer, New York.

Antonelli, C., Foray, D., Hall, B., Steinmüller, W.E. (Eds.), (2006). New Frontiers in the Economics of Innovation and New Technology, Essays in Honor of Paul A. David. Edward Elgar Publishing, Cheltenham, UK.

Argote, L., Epple, D. (1990). "Learning curves in manufacturing". Science 247 (4945), 920–924.

Arora, A., Gambardella, A. (1994). "The changing technology of technological change: General and abstract knowledge and the division of innovative labour". Research Policy 23, 523–532.

Arora, A., Fosfuri, A., Gambardella, A. (2002). Markets for Technology. MIT Press, Cambridge, MA.

Arora, A., Gambardella, A., Klepper, S. (2006). "Organizational capabilities and the rise of the software industry in the emerging economies: Lessons from the history of some US industries". In: Arora, A., Gambardella, G. (Eds.), From Underdogs to Tigers. Oxford University Press, Oxford, pp. 171–206.

Arrow, K.J. (1962a). "Economics of welfare and the allocation of resources for invention". In: Nelson, R.R. (Ed.), The Rate and Direction of Inventive Activity. Princeton University Press, Princeton, NJ, pp. 609–625.

Arrow, K. (1962b). "The economic implications of learning by doing". Review of Economic Studies 29, 155–173.

Arrow, K. (1996). "Technical information and industrial structure". Industrial and Corporate Change 5 (2), 645–652.

Arthur, W.B. (1988). "Competing technologies: An overview". In: Dosi, G., Freeman, C., Nelson, R., Silverberg, G., Soete, L. (Eds.), Technical Change and Economic Theory. Pinter Publishing, London, pp. 590–607.

Arthur, W.B. (1989). "Competing technologies, increasing returns, and lock-in by historical events". Economic Journal 99 (394), 116–131.

Arthur, W.B. (2007). "The structure of invention". Research Policy 36 (2), 274–287.

Arthur, W.B., Ermoliev, Y., Kaniovski, Y. (1987). "Path-dependent processes and the emergence of macro-structure". European Journal of Operational Research 30 (3), 294–303.

Arundel, A., van de Paal, G., Soete, L. (1995). Innovation strategies of Europe's largest firms. Results of the PACE survey. European Innovation Monitoring System, Report No. 23, European Commission, Brussels.

Atkinson, A.B., Stiglitz, J.E. (1969). "A new view of technological change". Economic Journal 79 (315), 573–578.

Audretsch, D.B. (1997). "Technological regimes, industrial demography and the evolution of industrial structures". Industrial and Corporate Change 6 (1), 49–82.

Auerswald, P., Kaufmann, S., Lobo, J., Shell, K. (2000). “The production recipe approach to modelling technological innovation: An application to learning by doing”. Journal of Economic Dynamics and Control 24, 389–450.
Augier, M., March, J. (2000). “Roots and branches of organizational economics”. Industrial and Corporate Change 9 (Special Issue), 555–788.
Augier, M., March, J. (2002). The Economics of Choice, Change and Organizations: Essays in Memory of Richard M. Cyert. Edward Elgar Publishing, Cheltenham, UK.
Aversi, R., Dosi, G., Fagiolo, G., Meacci, M., Olivetti, C. (1999). “Demand Dynamics with Socially Evolving Preferences”. Industrial and Corporate Change 8 (2), 353–408.
Axtell, R.L. (2001). “Zipf distribution of U.S. firm sizes”. Science 293, 1818–1820.
Baily, M., Hulten, C., Campbell, D. (1992). The distribution of productivity in manufacturing plants. Brookings Papers on Economic Activities: MicroeconomicsBrookings Institution, Washington, DC pp. 187–249.
Baily, M., Bartelsman, E., Haltiwanger, J. (1996). “Downsizing and productivity growth: Myth or reality?” Small Business Economics 8 (4), 259–278.
Balconi, M. (2002). “Tacitness, codification of technological knowledge and the organisation of industry”. Research Policy 31 (3), 357–379.
Baldwin, C.Y., Clark, K.B. (2000). Design Rules. MIT Press, Cambridge, MA.
Baldwin, J.R. (1995). The Dynamics of Industrial Competition: A North American Perspective. Cambridge University Press, New York, NY.
Baldwin, J.R., Gu, W. (2006). “Plant turnover and productivity growth in Canadian manufacturing”. Industrial and Corporate Change 15 (3), 417–465.
Baloff, N. (1971). “Extension of the learning curve. Some empirical results”. Operation Research Quarterly 22, 329–340.
Barna, T. (1962). Investment and Growth Policies in British Industrial Firms. Cambridge University Press, Cambridge.
Bartelsman, E., Doms, M. (2000). “Understanding productivity: Lessons from longitudinal microdata”. Journal of Economic Literature 38, 569–594.
Bartelsman, E., Scarpetta, S., Schivardi, F. (2005). “Comparative analysis of firm demographics and survival: Evidence from micro-level sources in OECD countries”. Industrial and Corporate Change 14, 365–391.
Basalla, G. (1988). The Evolution of Technology. Cambridge University Press, Cambridge.
Bassanini, A., Dosi, G. (2001). “Heterogenous agents, complementarities and diffusion: Do increasing returns imply convergence to international technological monopolies?” In: Delli Gatti, D., Gallegati, M., Kirman, A. (Eds.), Market Structure, Aggregation, and Heterogeneity. Cambridge University Press, Cambridge.
Bassanini, A., Dosi, G. (2006). “Competing technologies, technological monopolies and the rate of convergence to a stable market structure”. In: Antonelli, C., Foray, D., Hall, B.H., Steinmueller, E.W. (Eds.), New Frontiers in the Economics of Innovation and New Technology, Essays in Honor of Paul A. David. Edward Elgar Publishing, Cheltenham, UK, pp. 23–59.
Beardsley, G., Mansfield, E. (1978). “A note on the accuracy of industrial forecasts of the profitability of new products and processes”. Journal of Business 51, 127–135.
Becker, M.C., Lazaric, N. (Eds.), (2009). Recent Empirical Advances on Organizational Routines. Edward Elgar Publishing, Cheltenham, UK.
Becker, M.C., Lazaric, N., Nelson, R.R., Winter, S.G. (2005). “Applying organizational routines in analyzing organizations”. Industrial and Corporate Change 14 (5), 775–791.
Bergek, A., Tell, F., Berggren, C., Watson, J. (2008). “Technological capabilities and late shakeouts: Industrial dynamics in the advanced gas turbine industry, 1987–2002”. Industrial and Corporate Change 17, 335–392.
Binswanger, H., Ruttan, V. (1978). Induced Innovation. Johns Hopkins University Press, Baltimore, MD.
Bonaccorsi, A., Giuri, P. (2000). “When shakeout doesn’t occur. The evolution of the turboprop engine industry”. Research Policy 29, 847–870.
Bonaccorsi, A., Giuri, P., Pierotti, F. (2005). “Technological frontiers and competition in multi-technology sectors. Micro evidence from the aero-engine industries”. Economics of Innovation and New Technology 14, 23–42.
Bottazzi, G., Secchi, A. (2003). “Why are distributions of firm growth rates tent-shaped?” Economics Letters 80, 415–420.
Bottazzi, G., Secchi, A. (2005). “Growth and diversification patterns of the worldwide pharmaceutical industry”. Review of Industrial Organization 26, 195–216.
Bottazzi, G., Secchi, A. (2006). “Explaining the distribution of firms growth rates”. RAND Journal of Economics 37, 234–263.

Bottazzi, G., Dosi, G., Lippi, M., Pammolli, F., Riccaboni, M. (2001a). "Innovation and corporate growth in the evolution of the drug industry". International Journal of Industrial Organization 19, 1161–1187.
Bottazzi, G., Dosi, G., Rocchetti, G. (2001b). "Modes of knowledge accumulation, entry regimes and patterns of industrial evolution". Industrial and Corporate Change 10, 609–638.
Bottazzi, G., Cefis, E., Dosi, G. (2002). "Corporate growth and industrial structure. Some evidence from the Italian manufacturing industries". Industrial and Corporate Change 11, 705–723.
Bottazzi, G., Dosi, G., Cefis, E., Secchi, A. (2007). "Invariances and diversities in the evolution of manufacturing industries". Small Business Economics 29 (1), 137–159.
Bottazzi, G., Dosi, G., Jacoby, N., Secchi, A., Tamagni, F. (2009). Corporate performance and market selection. LEM Working Paper Series 2009/13, Sant'Anna School of Advanced Studies, Pisa, Italy, forthcoming on Industrial and Corporate Change (2010).
Boyer, R., Saillard, Y. (Eds.) (2002). Regulation Theory. The State of the Art. Routledge, London and New York.
Bradshaw, G.F. (1992). "The airplane and the logic of invention". In: Giere, R.N. (Ed.), Cognitive Models of Science. The University of Minnesota Press, Minneapolis, MN, pp. 239–250.
Breschi, S., Malerba, F., Orsenigo, L. (2000). "Technological regimes and Schumpeterian patterns of innovation". Economic Journal 110, 388–410.
Breschi, S., Lissoni, F., Malerba, F. (2003). "Knowledge-relatedness in firm technological diversification". Research Policy 32 (1), 69–87.
Bresnahan, T.F., Trajtenberg, M. (1995). "General purpose technologies: 'Engines of growth'?" Journal of Econometrics 65 (1), 83–108.
Bresnahan, T., Greenstein, S., Henderson, R. (2008). Schumpeterian competition and diseconomies of scope; illustrations from leading historical firms in computing. Kellogg Institute WP.
Brown, J.D., Earle, J.S., Telegdy, A. (2006). "The Productivity Effects of Privatization: Longitudinal Estimates from Hungary, Romania, Russia, and Ukraine". Journal of Political Economy 114 (1), 61–99.
Brynjolfsson, E., Hitt, L.M. (2000). "Beyond Computation: Information technology, organizational transformation and business performance". Journal of Economic Perspectives 14, 3–48.
Burns, A.F. (1934). Production Trends in the United States Since 1870. NBER, New York, NY.
Bush, V. (1945). Science: The Endless Frontier. Government Printing Office, Washington, DC.
Cantner, U., Krüger, J. (2004). "Geroski's stylized facts and mobility in large German manufacturing firms". International Journal of Industrial Organization 24, 267–283.
Cantner, U., Krüger, J., Rhein, K.V. (2009). "Knowledge and creative destruction over the industry life cycle. The case of the German automobile industry". Economica 76, 132–148.
Carroll, G.R. (1997). "Long-term evolutionary changes in organizational populations: Theory, models and empirical findings". Industrial and Corporate Change 6 (1), 119–143.
Carroll, G.R., Hannan, M.T. (2000). The Demography of Corporations and Industries. Princeton University Press, Princeton, NJ.
Castaldi, C., Fontana, R., Nuvolari, A. (2009). "'Chariots of fire': The evolution of tank technology, 1915–1945". Journal of Evolutionary Economics 19 (4), 545–566.
Cefis, E. (2003a). "Persistence in innovation and profitability". Rivista Internazionale di Scienze Sociali 110, 19–37.
Cefis, E. (2003b). "Is there persistence in innovative activities?" International Journal of Industrial Organization 21, 482–515.
Cefis, E., Ciccarelli, M. (2005). "Profit differentials and innovation". Economics of Innovation and New Technologies 14 (1–2), 43–61.
Cefis, E., Orsenigo, L. (2001). "The persistence of innovative activities: A cross-country and cross-sector comparative analysis". Research Policy 30, 1139–1158.
Chandler, A. (1992). "Organizational capabilities and the economic history of the industrial enterprise". Journal of Economic Perspectives 6 (3), 79–100.
Chandler, A., Galambos, L. (1970). "The development of large-scale economic organizations in modern America". Journal of Economic History 30 (1), 201–210.
Chataway, J., Tait, J., Wield, D. (2004). "Understanding company R&D strategies in agro-biotechnology: Trajectories and blind spots". Research Policy 33 (6–7), 1041–1057.
Chiaromonte, F., Dosi, G. (1993). "Heterogeneity, competition, and macroeconomic dynamics". Structural Change and Economic Dynamics 4 (1), 39–63.

Cimoli, M., Soete, L. (1992). "A generalized technology gap trade model". Economie Appliquée, vol XLV, no. 3, pp. 33–54.
Cimoli, M., Dosi, G. (1995). "Technological paradigms, patterns of learning and development: An introductory roadmap". Journal of Evolutionary Economics 5 (3), 243–268.
Cimoli, M., Dosi, G., Stiglitz, J.E. (Eds.), (2009). Industrial Policy and Development: The Political Economy of Capabilities Accumulation. Oxford University Press, Oxford.
Coad, A. (2008). The Growth of Firms: A Survey of Theories and Empirical Evidence. Edward Elgar Publishing, Cheltenham, UK.
Coad, A., Rao, R. (2008). "Innovation and firm growth in high-tech sectors: A quantile regression approach". Research Policy 37 (4), 633–648.
Cohen, W., Levin, R. (1989). "Empirical studies of innovation and market structure". In: Schmalensee, R., Willig, R. (Eds.), Handbook of Industrial Organization, vol. 2. Elsevier, Amsterdam.
Cohen, W.M., Levinthal, D.A. (1990). "Absorptive capacity: A new perspective on learning and innovation". Administrative Science Quarterly 35, 128–152.
Cohen, M.D., Burkhart, R., Dosi, G., Egidi, M., Marengo, L., Warglien, M., Winter, S. (1996). "Routines and other recurring action patterns of organizations: Contemporary research issues". Industrial and Corporate Change 5 (3), 653–698.
Cohen, W., Nelson, R.R., Walsh, J.P. (2002). "Links and impacts: The influence of public research on industrial R&D". Management Science 48 (1), 1–23.
Conley, P. (1970). "Experience curves as a planning tool". IEEE Spectrum 7 (6), 63–68.
Conlisk, J. (1989). "An aggregate model of technical change". Quarterly Journal of Economics 104, 787–821.
Conoway, R., Schultz, A. (1959). "The manufacturing progress function". Journal of Industrial Engineering 10, 39–53.
Consoli, D. (2005). "The dynamics of technological change in UK retail banking services: An evolutionary perspective". Research Policy 34 (4), 461–480.
Constant, E. (1980). The Origins of the Turbojet Revolution. Johns Hopkins University Press, Baltimore, MD.
Coriat, B., Dosi, G. (1998). "Learning how to govern and learning how to solve problems: On the co-evolution of competences, conflicts, and organizational routines". In: Chandler, A., Hagström, P., Sölvell, O. (Eds.), The Dynamic Firm. Oxford University Press, Oxford, pp. 103–134.
Cowan, R. (2001). "Expert systems: Aspects of and limitations to the codifiability of knowledge". Research Policy 30, 1355–1372.
Cowan, R., David, P.A., Foray, D. (2000). "The explicit economics of knowledge codification and tacitness". Industrial and Corporate Change 9 (2), 211–253.
Cubbin, J., Geroski, P. (1987). "The convergence in profits in the long-run: Inter-firm and inter-industry comparisons". Journal of Industrial Economics 35, 427–442.
Cyert, R.M., March, J.G. (1992). A Behavioral Theory of the Firm (second ed.). Basil Blackwell Publishing, Cambridge.
Dasgupta, P., David, P.A. (1994). "Towards a new economics of science". Research Policy 23, 487–521.
David, P.A. (1975). Technical Choice, Innovation and Economic Growth. Cambridge University Press, Cambridge.
David, P.A. (1985). "Clio and the economics of QWERTY". American Economic Review 75, 332–337.
David, P.A. (1988). Path dependence: Putting the past into the future of economics. Technical Report No. 533, Institute for Mathematical Studies in the Social Sciences, Stanford, CA.
David, P.A. (1989). A paradigm for historical economics: Path dependence and predictability in dynamic systems with local network externalities. Working PaperStanford University Press, Stanford, CA.
David, P.A. (1990). "The dynamo and the computer: An historical perspective on the modern productivity paradox". American Economic Review 80 (2), 355–361.
David, P.A. (1992). "Heroes, herds and hysteresis in technological history". Industrial and Corporate Change 1 (1), 129–179.
David, P.A. (1993). "Knowledge property and the system dynamics of technological change". In: Summers, L., Shah, S. (Eds.), Proceedings of the World Bank Conference on Development Economics. The World Bank, Washington, DC, pp. 215–248.
David, P.A. (2001a). From keeping nature's secrets to the institutionalization of open science. Discussion Papers in Economic and Social History, University of Oxford, Oxford.
David, P.A. (2001b). "Path dependence, its critics and the quest for 'historical economics'". In: Garrouste, P., Ioannides, S. (Eds.), Evolution and Path Dependence in Economic Ideas: Past and Present. Edward Elgar Publishing, Cheltenham, UK.
David, P.A. (2004). "Understanding the emergence of 'open science' institutions: Functionalist economics in historical context". Industrial and Corporate Change 13 (3), 571–589.
David, P.A. (2005). "Path dependence in economic processes: Implications for policy analysis in dynamical system contexts". In: Dopfer, K. (Ed.), The Evolutionary Foundations of Economics. Cambridge University Press, Cambridge.

David, P.A., Hall, B. (2006). "Property and the pursuit of knowledge: IPR issues affecting scientific research". Research Policy 35 (6), 767–771.

David, P.A., Wright, G. (1997). "Increasing returns and the genesis of American resource abundance". Industrial and Corporate Change 6 (2), 203–245.

Dawid, H. (2006). "Agent-based models of innovation and technological change". In: Tesfatsion, L., Judd, K. (Eds.), Handbook of Computational Economics, vol. 2. Elsevier, Amsterdam, pp. 1235–1272.

Delli Gatti, D., Gallegati, M., Kirman, A. (Eds.), (2001). Market Structure, Aggregation and Heterogeneity. Cambridge University Press, Cambridge.

Demirel, P., Mazzucato, M. (2008). Does market selection reward innovators? R&D, patents and growth in the U.S. pharmaceutical industry. IKD Working Paper No. 33, Open University, London.

Dew, N. (2006). "Incommensurate technological paradigms? Quarreling in the RFID industry". Industrial and Corporate Change 15 (5), 785–810.

Dopfer, K. (Ed.), (2005). Principles of Evolutionary Economics. Cambridge University Press, Cambridge.

Dosi, G. (1982). "Technological paradigms and technological trajectories. A suggested interpretation of the determinants and directions of technical change". Research Policy 11, 147–162.

Dosi, G. (1984). Technical Change and Industrial Transformation. Macmillan, London.

Dosi, G. (1988). "Sources, procedures and microeconomic effects of innovation". Journal of Economic Literature 26 (3), 1120–1171.

Dosi, G. (1991). "The research on innovation diffusion: An assessment". In: Nakicenovic, N., Grübler, A. (Eds.), Diffusion of Technologies and Social Behavior. Springer, Laxenburg.

Dosi, G. (1997). "Opportunities, incentives and the collective patterns of technical change". Economic Journal 107 (444), 1530–1547.

Dosi, G. (2007). "Statistical regularities in the evolution of industries. A guide through some evidence and challenges for the theory". In: Malerba, F., Brusoni, S. (Eds.), Perspectives on Innovation. Cambridge University Press, Cambridge.

Dosi, G., Egidi, M. (1991). "Substantive and procedural uncertainty. An exploration of economic behaviours in changing environments". Journal of Evolutionary Economics 1 (2), 145–168.

Dosi, G., Grazzi, M. (2006). "Technologies as problem-solving procedures and technologies as input–output relations: Some perspectives on the theory of production". Industrial and Corporate Change 15 (1), 173–202.

Dosi, G., Kaniovski, Y. (1994). "On "Badly Behaved" Dynamics. Some applications of generalized urn schemes to technological and economic change". Journal of Evolutionary Economics 4 (2), 93–123.

Dosi, G., Lovallo, D. (1997). "Rational entrepreneurs or optimistic martyrs? Some considerations on technological regimes, corporate entries and the evolutionary role of decision biases". In: Garud, R., Nayyar, P.R., Shapira, Z.B. (Eds.), Technological Innovation Oversights and Foresights. Cambridge University Press, Cambridge.

Dosi, G., Nelson, R.R. (1994). "An introduction to evolutionary theories in economics". Journal of Evolutionary Economics 4 (3), 153–172.

Dosi, G., Winter, S.G. (2002). "Interpreting economic change: Evolution, structures and games". In: Augier, M., March, J. (Eds.), The Economics of Choice, Change, and Organizations. Edward Elgar Publishing, Cheltenham, UK.

Dosi, G., Freeman, C., Nelson, R.R., Silverberg, G., Soete, L. (Eds.), (1988). Technical Change and Economic Theory. Pinter Publishing, London.

Dosi, G., Pavitt, K., Soete, L. (1990). The Economics of Technical Change and International Trade. Wheatsheaf/New York University Press, Brighton, UK/New York, NY.

Dosi, G., Fabiani, S., Aversi, R., Meacci, M. (1994a). "The dynamics of international differentiation: A multi-country evolutionary model". Industrial and Corporate Change 2 (3), 225–241.

Dosi, G., Freeman, C., Fabiani, S. (1994b). "The process of economic development. Introducing some stylized facts and theories on technologies, firms and institutions". Industrial and Corporate Change 3 (1), 1–45.

Dosi, G., Marsili, O., Orsenigo, L., Salvatore, R. (1995). "Learning, market selection and the evolution of industrial structures". Small Business Economics 7, 411–436.

Dosi, G., Malerba, F., Marsili, O., Orsenigo, L. (1997). "Industrial structures and dynamics: Evidence, interpretations and puzzles". Industrial and Corporate Change 6, 3–24.

Dosi, G., Nelson, R.R., Winter, S. (Eds.), (2000). The Nature and Dynamics of Organizational Capabilities. Oxford University Press, Oxford.

Dosi, G., Levinthal, D., Marengo, L. (2003). "Bridging contested terrain: Linking incentive-based and learning perspectives on organizational evolution". Industrial and Corporate Change 12 (2), 413–436.

Dosi, G., Marengo, L., Fagiolo, G. (2005a). "Learning in evolutionary environments". In: Dopfer, K. (Ed.), The Evolutionary Foundations of Economics. Cambridge University Press, Cambridge, pp. 255–328.

Dosi, G., Orsenigo, L., Sylos Labini, M. (2005b). "Technology and the economy". In: Smelser, N.J., Swedberg, R. (Eds.), The Handbook of Economic Sociology. (second ed.). Princeton University Press/Russell Sage Foundation, Princeton, NJ.

Dosi, G., Fagiolo, G., Roventini, A. (2006a). "An evolutionary model of endogenous business cycles". Computational Economics 27 (1), 3–34.

Dosi, G., Llerena, P., Sylos Labini, M. (2006b). "Science–technology–industry links and the 'European paradox': Some notes on the dynamics of scientific and technological research in Europe". Research Policy 35 (10), 1450–1464.

Dosi, G., Marengo, L., Pasquali, C. (2006c). "How much should society fuel the greed of innovators? On the relations between appropriability, opportunities and rates of innovation". Research Policy 35 (8), 1110–1121.

Dosi, G., Faillo, M., Marengo, L. (2008a). "Organizational capabilities, patterns of knowledge accumulation and governance structures in business firms: An introduction". Organization Studies 29 (8), 1165–1185.

Dosi, G., Fagiolo, G., Roventini, A. (2008b). Schumpeter meeting Keynes: A policy-friendly model of endogenous growth and business cycles. LEM Working Paper Series, 2008/21, Sann't Anna School of Advanced Studies, Pisa, Italy, forthcoming in Journal of Economic Dynamics and Control, 2010.

Dosi, G., Gambardella, A., Grazzi, M., Orsenigo, L. (2008c). "Technological revolutions and the evolution of industrial structures: Assessing the impact of new technologies upon the size and boundaries of firms". Capitalism and Society 3 (1).

Dutton, J.M., Thomas, A. (1984). "Treating progress functions as a managerial opportunity". Academy of Management Review 9 (2), 235–247.

Ericson, R., Pakes, A. (1995). "Markov perfect industry dynamics: A framework for empirical work". Review of Economic Studies 62 (1), 53–82.

Evans, D.S. (1987). "The relationship between firm growth, size and age: Estimates for 100 manufacturing industries". Journal of Industrial Economics 35 (4), 567–581.

Fagerberg, J. (1994). "Technology and international differences in growth rates". Journal of Economic Literature 32 (3), 1147–1175.

Fagerberg, I., Mowery, D.C., Nelson, R.R. (Eds.), (2005). The Oxford Handbook of Innovation. Oxford University Press, Oxford.

Fagiolo, G., Dosi, G. (2003). "Exploitation, exploration and innovation in a model of endogenous growth with locally interacting agents". Structural Change and Economic Dynamics 14, 237–273.

Field, A.J. (2008). "Does Economic History Need GPTs?" Available at http://ssrn.com/abstract=1275023.

Fisher, R.A. (1930). The General Theory of Natural Selection. Clarendon Press, Oxford.

Fleck, J. (1988). "Innofusion or diffusation? The nature of technological developments in robotics". Programme on Information and Communications Technologies (PICT) Working Paper, Edinburgh.

Foss, N.J., Mahnke, V. (Eds.), (2000). Competence, Governance, and Entrepreneurship: Advances in Economic Strategy Research. Oxford University Press, Oxford.

Foster, L., Haltiwanger, J., Krizan, C.J. (2001). "Aggregate productivity growth: Lessons from microeconomic evidence". In: Dean, E., Harper, M., Hulten, C. (Eds.), New Developments in Productivity Analysis. University of Chicago Press, Chicago, IL.

Foster, L., Haltiwanger, J., Syverson, J. (2008). "Reallocation, firm turnover, and efficiency: Selection on productivity or profitability?" American Economic Review 98 (1), 394–425.

Freeman, C. (1982). The Economics of Industrial Innovation (second ed.). Frances Pinter Publishing, London.

Freeman, C. (1993). "The 'National System of Innovation' in historical perspective". Cambridge Journal of Economics 19 (1), 5–24.

Freeman, C. (1994). "The economics of technical change". Cambridge Journal of Economics 18, 463–514.

Freeman, C. (2008). Systems of Innovation: Selected Essays in Evolutionary Economics. Edward Elgar Publishing, Cheltenham, UK.

Freeman, C., Louça, F. (2001). As Time Goes By: The Information Revolution and the Industrial Revolutions in Historical Perspective. Oxford University Press, Oxford.

Freeman, C., Perez, C. (1988). "Structural crises of adjustment: Business cycles and investment behavior". In: Dosi, G., Freeman, R., Nelson, R., Silverberg, G., Soete, L. (Eds.), Technical Change and Economic Theory. Pinter Publishing, London.

Freeman, C., Soete, L. (1997). The Economics of Industrial Innovation (third ed.). Pinter Publishing, London.

Frenken, K., Leydesdorff, L. (2000). “Scaling trajectories in civil aircraft (1913–1997)”. Research Policy 28, 469–488.

Frenken, K., Nuvolari, A. (2004). “The early development of the steam engine: An evolutionary interpretation using complexity theory”. Industrial and Corporate Change 13, 419–450.

Frenken, K., Saviotti, P.P., Trommetter, M. (1999). “Variety and niche creation in aircraft, helicopters, motorcycles and microcomputers”. Research Policy 28 (5), 469–488.

Gary, M.S., Dosi, G., Lovallo, D. (2008). “Boom and bust behavior: On the persistence of strategic decision biases”. In: Hodgkinson, G.P., Starbuck, W.H. (Eds.), The Oxford Handbook of Organizational Decision Making. Oxford University Press, Oxford.

Georgescu-Roegen, N. (1970). “The economics of production”. American Economic Review 60 (2), 1–9.

Geroski, P.A. (1998). “An applied econometrician’s view of large company performance”. Review of Industrial Organization 13, 271–293.

Geroski, P.A. (2000). “Models of technology diffusion”. Research Policy 29, 603–625.

Geroski, P.A., Jacquemin, A. (1988). “The persistence of profits: A European comparison”. Economic Journal 98, 357–389.

Geroski, P.A., Mazzucato, M. (2002). “Learning and the sources of corporate growth”. Industrial and Corporate Change 11, 623–644.

Geroski, P.A., Machin, S., Van Reenen, J. (1993). “The profitability of innovating firms”. RAND Journal of Economics 24, 198–211.

Geroski, P.A., Machin, S., Walters, C. (1997). “Corporate growth and profitability”. Journal of Industrial Economics 45 (2), 171–189.

Geuna, A., Salter, A., Steinmuller, W.E. (Eds.), (2003). Science and Innovation: Rethinking the Rationale for Funding and Governance. Edward Elgar Publishing, Cheltenham, UK.

Giuri, P., Tomasi, C., Dosi, G. (2007). L’industria aerospaziale. Innovazione, tecnologia e strategia economica. Il Sole 24 Ore e Fondazione Cotec, Milan.

Goddard, J.A., Wilson, J. O. S. (1999). “The persistence of profit: As new empirical interpretation”. International Journal of Industrial Organization 17, 663–687.

Gordon, T.J., Munson, T.R. (1981). Research into Technology Output Measures. The Futures Group, Glastonbury, CT.

Granstrand, O. (1998). “Toward a theory of the technology-based firm”. Research Policy 27, 465–489.

Granstrand, O. (1999). The Economics and Management of Intellectual Property. Edward Elgar Publishing, Cheltenham, UK.

Granstrand, O. (2005). “Innovation and intellectual property rights”. In: Fagerberg, J., Mowery, D.C., Nelson, R.R. (Eds.), The Oxford Handbook of Innovation. Oxford University Press, Oxford, pp. 266–290.

Greenwald, B., Stiglitz, J. (1986). “Externalities in economies with imperfect information and incomplete markets”. Quarterly Journal of Economics 101 (2), 229–264.

Griliches, Z. (1957). "Hybrid Corn: An Exploration in the Economics of Technological Change". Econometrica, 25, 501–522.

Griliches, Z., Mairesse, J. (1997). “Production function: The search for identification”. In: Strøm, S. (Ed.), Econometrics and Economic Theory in the Twentieth Century: The Ragnar Frisch Centennial Symposium. Cambridge University Press, Cambridge.

Grimaldi, R., Torrisi, S. (2001). “Codified-tacit and general-specific knowledge in the division of labour among firms. A study of the software industry”. Research Policy 30 (9), 1425–1442.

Gritsevskyi, A., Nakicenovic, N. (2000). “Modeling uncertainty of induced technological change”. Energy Policy 28, 907–921.

Grupp, H. (1992). Dynamics of Science-Based Innovation. Springer, Berlin.

Gschwandtner, A. (2004). “Profit persistence in the “very” long run: Evidence from survivors and exiters”. Vienna Economics Papers 0401, University of Vienna, Department of Economics.

Hall, B.H. (1987). “The relationship between firm size and firm growth in the U.S. manufacturing sector”. Journal of Industrial Economics 3 (4), 583–606.

Hall, B.H. (2005). “Innovation and diffusion”. In: Fagerberg, J., Mowery, D.C., Nelson, R.R. (Eds.), The Oxford Handbook of Innovation. Oxford University Press, Oxford.

Hanusch, H., Pyka, A. (2007). Elgar Companion to Neo-Schumpeterian Economics. Edward Elgar Publishing, Cheltenham, UK.

Hart, P.E., Prais, J.S. (1956). “The Analysis of Business Concentration”. Journal of the Royal Statistical Society 119, 150–191.

Helfat, C. (Ed.), (2003). The SMS Blackwell Handbook of Organizational Capabilities Emergence, Development, and Change. Blackwell Publishing, London.

Helfat, C., Finkelstein, S., Mitchell, W., Peteraf, M.A., Singh, H., Teece, D.J., Winter, S.G. (2007). Dynamic Capabilities: Understanding Strategic Change in Organizations. Blackwell Publishing, Oxford.
Heller, M., Eisenberg, R. (1998). “Can patents deter innovation? The anti-commons in biomedical research”. Science 280, 698–701.
Henderson, R.M., Clark, K.B. (1990). “Architectural innovation: The reconfiguration of existing product technologies and the failure of established firms”. Administrative Science Quarterly 35, 9–30.
Hodgson, G.M. (1999). Evolution and Institutions: On Evolutionary Economics and the Evolution of Economics. Edward Elgar Publishing, Cheltenham, UK.
Hopenhein, H.A. (1992). “Entry, exit and firm dynamics in long run equilibrium”. Econometrica 60 (5), 1127–1150.
Hopkins, M.M., Martin, P.A., Nightingale, P., Kraft, A., Mahdi, S. (2007). “The myth of the biotech revolution: An assessment of technological, clinical and organizational change”. Research Policy 36 (4), 566–589.
Hughes, T.P. (1983). Networks of Power: Electrification in Western Society. Johns Hopkins University Press, Baltimore, MD.
Ijiri, Y., Simon, H.A. (1977). Skew Distributions and the Sizes of Business Firms. North-Holland, Amsterdam.
Iwai, K. (1984a). “Schumpeterian dynamics, Part I”. Journal of Economic Behavior & Organization 5, 159–190.
Iwai, K. (1984b). “Schumpeterian dynamics, Part II”. Journal of Economic Behavior & Organization 5, 321–351.
Jaffe, A.B. (2000). “The U.S. patent system in transition: Policy innovation and the innovation process”. Research Policy 29 (4–5), 531–577.
Jensen, B., McGuckin, H. (1997). “Firm performance and evolution: Empirical regularities in the US micro data”. Industrial and Corporate Change 6 (1), 25–47.
Jovanovic, B. (1982). “Selection and the evolution of industry”. Econometrica 50 (3), 649–670.
Jovanovic, B., Rousseau, P.L. (2002). “Moore’s law and learning by doing”. Review of Economic Dynamics 5 (2), 346–375.
Kauffman, S.A. (1993). The Origins of Order: Self-Organization and Selection in Evolution. Oxford University Press, Oxford.
Kauffman, S.A., Levin, S. (1987). “Toward a general theory of adaptive walks on rugged landscapes”. Journal of Theoretical Biology 128, 11–45.
Kerker, M. (1961). “Science and the steam engine”. Technology and Culture 2, 381–390.
Kirman, A.P. (2001). “Market organization and individual behavior: Evidence from fish markets”. In: Rauch, J.E., Casella, A. (Eds.), Networks and Markets. Russell Sage Foundation, New York, NY, pp. 155–195.
Klepper, S. (1997). “Industry life cycles”. Industrial and Corporate Change 6 (1), 145–181.
Klepper, S., Simons, K.L. (2005). “Industry shakeouts and technological change”. International Journal of Industrial Organization 23, 23–43.
Klevorick, A.K., Levin, R.C., Nelson, R.R., Winter, S.G. (1995). “On the sources and significance of interindustry differences in technological opportunities”. Research Policy 24, 185–205.
Kline, S.J., Rosenberg, N. (1986). “An overview of innovation”. In: Landau, R., Rosenberg, N. (Eds.), The Positive Sum Strategies: Harnessing Technology for Economic Growth. National Academic Press, Washington, DC, pp. 275–305.
Kuhn, T. (1962). The Structure of Scientific Revolutions. University of Chicago Press, Chicago, IL.
Kumar, M.S. (1985). “Growth, acquisition activity and firm size: Evidence from the United Kingdom”. Journal of Industrial Economics 33, 171–196.
Kuznets, S. (1972). Modern Economic Growth. Yale University Press, New Haven, CT.
Kwasnicki, W., Kwasnicka, H. (1992), “Market, innovation, competition: An evolutionary model of industrial dynamics”, Journal of Economic Behavior & Organization, 19 (3), 343–368.
Landes, D.S. (1969). The Unbound Prometheus. Cambridge University Press, Cambridge.
Landes, D.S. (1998). The Wealth and Poverty of Nations: Why Are Some So Rich and Others So Poor? W.W. Norton, New York, NY.
Lazaric, N., Lorenz, E. (Eds.), (2003). Knowledge, Learning and Routines. Edward Elgar Publishing, Cheltenham, UK.
Levin, R.C., Cohen, W.M., Mowery, D.C. (1985). “R&D appropriability, opportunity and market structure: New evidence on some Schumpeterian hypotheses”. American Economic Review Proceedings 75, 20–24.
Levinthal, D.A. (1997). “Adaptation on rugged landscapes”. Management Science 43, 934–950.
Levinthal, D.A., Warglien, M. (1999). “Landscape design: Designing for local action in complex worlds”. Organization Science 10 (3), 342–357.
Liebowitz, S.J., Margolis, S.E. (1995). “Path dependence, lock-in and history”. Journal of Law, Economics, and Organization 11, 205–226.

Lotti, F., Santarelli, E., Vivarelli, M. (2003). “Does Gibrat’s law hold in the case of young, small firms?” Journal of Evolutionary Economics 13 (2), 213–235.

Louça, F., Mendonça, S. (2002). “Steady change: The 200 largest U.S. manufacturing firms throughout the 20th century”. Industrial and Corporate Change 11 (4), 817–845.

Lucas, R.E. (1978). “On the size distribution of business firms”. Bell Journal of Economics 9, 508–523.

Lundberg, E. (1961). “Produktivitet och Räntabilitet”. P.A. Norstedt & Söner, Stockholm. Quoted in Arrow (1962b).

Lundvall, B.A. (1992). National Systems of Innovation: Towards a Theory of Innovation and Interactive Learning. Pinter Publishing, London.

MacDonald, A., Schrattenholzer, L. (2001). “Learning rates for energy technologies”. Energy Policy 29, 255–261.

Malerba, F. (2002). “Sectoral systems of innovation and production”. Research Policy 31 (2), 247–264.

Malerba, F. (Ed.), (2004). Sectoral System of Innovation: Concepts, Issues, and Analyses of Six Major Sectors in Europe. Cambridge University Press, Cambridge.

Malerba, F., Brusoni, S. (Eds.), (2007). Perspectives on Innovation. Cambridge University Press, Cambridge.

Malerba, F., Orsenigo, L. (1995). “Schumpeterian patterns of innovation”. Cambridge Journal of Economics 19 (1), 47–65.

Malerba, F., Orsenigo, L. (1996a). “Schumpeterian patterns of innovation are technology-specific”. Research Policy 25 (3), 451–478.

Malerba, F., Orsenigo, L. (1996b). “The dynamics and evolution of industries”. Industrial and Corporate Change 5, 51–87.

Malerba, F., Orsenigo, L. (1997). “Technological regimes and sectoral patterns of innovative activities”. Industrial and Corporate Change 6, 83–117.

Malerba, F., Nelson, R., Orsenigo, L., Winter, S. (1999). “History friendly models of industry evolution: The case of the computer industry”. Industrial and Corporate Change 8 (1), 3–40.

Malerba, F., Nelson, R., Orsenigo, L., Winter, S. (2007). “Demand, innovation, and the dynamics of market structure: The role of experimental users and diverse preferences”. Journal of Evolutionary Economics 17 (4), 371–399.

Malerba, F., Nelson, R., Orsenigo, L., Winter, S. (2008). “Vertical integration and dis-integration of computer firms: A history friendly model of the co-evolution of the computer and semiconductor industries”. Industrial and Corporate Change 17 (2), 197–231.

Mandeville, B. (1714). The Fable of the Bees, or, Private Vices, Public Benefits. Clarendon Press, Oxford Reprinted in Kaye, F.B. (Ed.) (1924). Mandeville’s Fable of the Bees: Or, Private Vices, Public Benefits. Clarendon Press, Oxford.

Mansfield, E. (1961). “Technical change and the rate of imitation”. Econometrica 29 (4), 741–766.

Mansfield, E. (1962). “Entry, Gibrat’s law, innovation and the growth of firms”. American Economic Review 52, 1023–1051.

Mansfield, E., Schwartz, M., Wagner, S. (1981). “Imitation costs and patents: An empirical study”. Economic Journal 91 (364), 907–918.

March, J. (1988). Decision and Organizations. Basil Blackwell Publishing, Oxford.

March, J., Simon, H. (1958). Organizations. Basil Blackwell Publishing, New York, NY (second ed., 1993).

Marengo, L., Dosi, G. (2006). “Division of labor, organizational coordination and market mechanisms in collective problem-solving”. Journal of Economic Behavior & Organization 58, 303–326.

Marengo, L., Dosi, G., Legrenzi, P., Pasquali, C. (2000). “The structure of problem-solving knowledge and the structure of organizations”. Industrial and Corporate Change 9, 757–788.

Marengo, L., Pasquali, C., Valente, M., Dosi, G. (2009). Appropriability, patents, and rates of innovation in complex products industries. LEM Working Paper Series, 2009/05, Sant’ Anna School of Advanced Studies, Pisa, Italy.

Marsili, O. (2001). The Anatomy and Evolution of Industries: Technological Change and Industrial Dynamics. Edward Elgar Publishing, Cheltenham, UK.

Marsili, O., Verspagen, B. (2002). “Technology and the dynamics of industrial structures: An empirical mapping of Dutch manufacturing”. Industrial and Corporate Change 11 (4), 791–815.

Marx, K. (1847). The Poverty of Philosophy (English version). Marx-Engels Institute, Moscow.

Mazzoleni, R., Nelson, R.R. (1998). “The benefits and costs of strong patent protection: A contribution to the current debate”. Research Policy 27 (3), 273–284.

Mazzucato, M. (2002). “The PC industry: New economy of early life cycle”. Review of Economic Dynamics 5, 318–345.

Merges, R.P., Nelson, R.R. (1994). “On limiting or encouraging rivalry in technical progress: The effect of patent scope decisions”. Journal of Economic Behavior & Organization 25 (1), 1–24.

Merton, R.K. (1973). The Sociology of Science: Theoretical and Empirical Investigations. University of Chicago Press, Chicago, IL.
Metcalfe, J.S. (1988). "The diffusion of innovations: An interpretative survey". In: Dosi, G., Freeman, C., Nelson, R., Silverberg, L., Stole, L. (Eds.), Technical Change and Economic Theory. Pinter Publishing, London, pp. 560–589.
Metcalfe, J.S. (1994). "Evolutionary economics and technology policy". Economic Journal 104 (425), 931–944.
Metcalfe, J.S. (1998). Evolutionary Economics and Creative Destruction. Routledge, London.
Metcalfe, J.S. (2005a). "Ed Mansfield and the diffusion of innovation: An evolutionary connection". Journal of Technology Transfer 30, 171–181.
Metcalfe, J.S. (2005b). "Evolutionary concepts in relation to evolutionary economics". In: Dopfer, K. (Ed.), The Evolutionary Foundations of Economics. Cambridge University Press, Cambridge.
Metcalfe, J.S., Foster, J., Ramlogan, R. (2005). "Adaptive economic growth". Cambridge Journal of Economics 30 (1), 7–32.
Mina, A., Ramlogan, R., Tampubolon, G., Metcalfe, J.S. (2007). "Mapping evolutionary trajectories: Applications to the growth and transformation of medical knowledge". Research Policy 36 (5), 789–806.
Mitchell, W.C. (1925). "Quantitative analysis in economic theory". American Economic Review 15 (1), 1–12.
Mokyr, J. (1990). The Lever of Riches: Technological Creativity and Economic Progress. Oxford University Press, Oxford.
Mokyr, J. (2002). The Gifts of Athena: Historical Origins of the Knowledge Economy. Princeton University Press, Princeton, NJ.
Mokyr, J. (2010). The contribution of economic history to the study of innovation and technical change: 1750–1914, this volume.
Montgomery, C. (1995). Resource-Based and Evolutionary Theories of the Firm. Kluwer, Boston, MA.
Morroni, M. (1992). Production Process and Technical Change. Cambridge University Press, Cambridge.
Mowery, D.C., Nelson, R.R. (Eds.), (1999). Sources of Industrial Leadership. Cambridge University Press, Cambridge.
Mowery, D.C., Rosenberg, N. (1982). Paths of Innovation, Technological Change in 20th Century America. Cambridge University Press, Cambridge.
Mowery, D.C., Rosenberg, N. (1989). Technology and the Pursuit of Economic Growth. Cambridge University Press, New York, NY.
Mowery, D.C., Rosenberg, N. (1979). "The influence of market demand upon innovation: A critical review of some recent empirical studies". Research Policy 8 (2), 102–153.
Mueller, D. (1986). Profits in the Long-Run. Cambridge University Press, Cambridge.
Mueller, D. (1990). The Dynamic of Company Profits. An International Comparison. Cambridge University Press, Cambridge.
Murmann, J.P. (2003). Knowledge and competitive advantage. Cambridge University Press, Cambridge.
Murmann, J.P., Frenken, K. (2006). "Toward a systematic framework for research on dominant designs, technological innovations, and industrial change". Research Policy 35 (7), 925–952.
Murray, F.E., Aghion, P., Dewatripont, M., Kolev, J., Stern, S. (2009). "Of mice and academics: Examining the effect of openness on innovation". NBER Working Paper Series, No. 14819.
Muth, J.F. (1986). "Search theory and the manufacturing progress function". Management Science 32, 948–962.
Nakicenovic, N., Grübler, A. (Eds.), (1991). Diffusion of Technologies and Social Behaviour. Springer, Heidelberg.
Needham, J. (1962–1963). "The pre-natal history of the steam engine". Transactions of the Newcomen Society 35, 3–58.
Nasbeth, L., Ray, G.F. (Eds.), (1974). The diffusion of new industrial processes. Cambridge University Press, Cambridge.
Neij, L. (1997). "Use of experience curves to analyse the prospects for diffusion and adoption of renewable energy technology". Energy Policy 25 (13), 1099–1107.
Nelson, R.R. (1959). "The simple economics of basic scientific research". Journal of Political Economy 67 (3), 297–306.
Nelson, R.R. (Ed.), (1962). The Rate and Direction of Inventive Activity. Princeton University Press, Princeton, NJ.
Nelson, R.R. (1968). "A diffusion model of international productivity differences in manufacturing industry". American Economic Review 58 (5), 1219–1248.
Nelson, R.R. (1981). "Research on productivity growth and productivity differences: Dead ends and new departures". Journal of Economic Literature 19 (3), 1029–1064.
Nelson, R.R. (1982). "The role of knowledge in R&D efficiency". Quarterly Journal of Economics 97 (3), 453–470.
Nelson, R.R. (1993). National Systems of Innovation: A Comparative Analysis. Oxford University Press, New York, NY.
Nelson, R.R. (1996). The Sources of Economic Growth. Harvard University Press, Cambridge, MA.
Nelson, R.R. (1998). "The agenda for growth theory: A different point of view". Cambridge Journal of Economics 22, 497–520.
Nelson, R.R. (1999). "The sources of industrial leadership: A perspective on industrial policy". De Economist 147, 1–18.
Nelson, R.R. (2003). "On the uneven evolution of human know-how". Research Policy 32 (6), 909–922.

Nelson, R.R. (2004). "The market economy, and the scientific commons". Research Policy 33 (3), 455–471.
Nelson, R.R. (2005). Technology, Institutions, and Economic Growth. Harvard University Press, Cambridge, MA.
Nelson, R.R. (2006). "Reflections on "The Simple Economics of Basic Scientific Research": Looking back and looking forward". Industrial and Corporate Change 15, 145–149.
Nelson, R.R. (2008a). "Factors affecting the powers of technological paradigms". Industrial and Corporate Change 17, 485–497.
Nelson, R.R. (2008b). "Why do firms differ and how does it matter? A revisitation". Seoul Journal of Economics 28, 607–619.
Nelson, R.R. (2008c). "What enables rapid economic progress? What are the needed institutions?" Research Policy 37 (1), 1–11.
Nelson, R.R., Nelson, K. (2002). "On the nature and evolution of human know-how". Research Policy 31, 719–733.
Nelson, R.R., Pack, H. (1999). "The Asian miracle and modern growth theory". Economic Journal 109 (457), 416–436.
Nelson, R., Sampat, B. (2001). "Making sense of institutions as a factor shaping economic performance". Journal of Economic Behavior & Organization 44, 31–54.
Nelson, R.R., Winter, S.G. (1977). "In search of a useful theory of innovation". Research Policy 6, 36–76.
Nelson, R.R., Winter, S.G. (1982). An Evolutionary Theory of Economic Change. Harvard University Press, Cambridge, MA.
Nelson, R.R., Winter, S.G. (2002). "Evolutionary theorizing in economics". Journal of Economic Perspectives 16 (2), 23–46.
Nelson, R.R., Wolff, E.N. (1997). "Factors behind cross-industry differences in technical progress". Structural Change and Economic Dynamics 8 (2), 205–220.
Nelson, R.R., Peterhausl, A., Sampat, B. (2004). "Why and how innovations get adopted: A tale of four models". Industrial and Corporate Change 13, 679–699.
Nightingale, P. (1998). "A cognitive model of innovation". Research Policy 27, 689–709.
Nightingale, P. (2003). "If Nelson and Winter are only half right about tacit knowledge, which half? A Searlian critique of "codification"" Industrial and Corporate Change 12, 149–183.
Nordhaus, W.D. (2007). "Two centuries of productivity growth in computing". Journal of Economic History 67 (1), 128–159.
Nuvolari, A. (2004). "Collective invention during the British industrial revolution: The case of the Cornish pumping engine". Cambridge Journal Economics 28, 347–363.
Nuvolari, A., Verspagen, B. (2009). "Technical choice, innovation and British steam engineering, 1800–1850". Economic History Review 63, 685–710.
Pasinetti, L.L. (1981). Structural Change and Economic Growth. A Theoretical Essay on the Dynamics of the Wealth of Nations. Cambridge University Press, Cambridge.
Pavitt, K. (1984). "Sectoral patterns of technical change: Towards a taxonomy and a theory". Research Policy 13, 343–373.
Pavitt, K. (1986). "'Chips' and 'Trajectories': How does the semiconductor influence the sources and directions of technical change?" In: MacLeod, R.M. (Ed.), Technology and the Human Prospect. Pinter Publishing, London.
Pavitt, K. (1987). "The objectives of technology policy". Science and Public Policy 14, 182–188.
Pavitt, K. (1999). Technology, Management and Systems of Innovation. Edward Elgar Publishing, Cheltenham, UK.
Pavitt, K. (2001). "Public policies to support basic research: What can the rest of the world learn from US theory and practice? (and what they should not learn)". Industrial and Corporate Change 10 (3), 761–779.
Pavitt, K. (2005). "Innovation processes". In: Fagerberg, J., Mowery, D.C., Nelson, R.R. (Eds.), The Oxford Handbook of Innovation. Oxford University Press, Oxford, pp. 86–114.
Perez, C. (1985). "Microelectronics, long waves and world structural change: New perspectives for developing countries". World Development 13, 441–463.
Perez, C. (2002). Technological revolutions and financial capital: The dynamics of bubbles and golden ages. Edward Elgar Publishing, Cheltenham, UK.
Perez, C. (2010). "Technological revolutions and techno-economic paradigms". Cambridge Journal of Economics 34, 185–202.
Polanyi, M. (1962). Personal Knowledge: Towards a Post-Critical Philosophy. University of Chicago Press, Chicago, IL.
Polanyi, M. (1967). The Tacit Dimension. Anchor Books, New York, NY.
Possas, M.L., Salles-Filho, S., Silveira, J.M. (1996). "An evolutionary approach to technological innovation in agriculture: Some preliminary remarks". Research Policy 25 (6), 933–945.
Power, L. (1998). "The missing link: Technology, investment and productivity". Review of Economics and Statistics 80, 300–313.
Prencipe, A., Tell, F. (2001). "Inter-project learning: Processes and outcomes of knowledge codification in project-based firms". Research Policy 30, 1373–1394.
Prencipe, A., Davies, A., Hobday, M. (Eds.), (2003). The Business of Systems Integration. Oxford University Press, Oxford.
Radner, R. (1992). "Hierarchy: The economics of managing". Journal of Economic Literature 30 (3), 1382–1415.

Radner, R. (1993). “The organization of decentralized information processing”. Econometrica 61 (5), 1109–1146.
Ray, G. F. (1989). “Full circle: The diffusion of technology”, Research Policy, Elsevier, 18 (1), 1–18.
Roberts, P.W. (1999). “Product innovation, product-market competition and persistent profitability in the U.S Pharmaceutical industry”. Strategic Management Journal 20, 655–670.
Romer, P.M. (1994). “The origins of endogenous growth”. Journal of Economic Perspectives 8 (1), 3–22.
Rosenberg, N. (1963). “Mandeville and Laissez-Faire”. Journal of the History of Ideas 24 (2), 183–196.
Rosenberg, N. (1972). “Factors affecting the diffusion of technology”. Explorations in Economic History 10, 3–33.
Rosenberg, N. (1976). Perspectives on Technology. Cambridge University Press, Cambridge.
Rosenberg, N. (1982). Inside the Black Box: Technology and Economics. Cambridge University Press, Cambridge.
Rosenberg, N. (1994). Exploring the Black Box: Technology, Economics, and History. Cambridge University Press, Cambridge.
Rosenberg, N. (1996). “Uncertainty and technological change”. In: Landau, R., Taylor, T., Wright, G. (Eds.), The Mosaic of Economic Growth. Stanford University Press, Stanford, CA.
Rosenberg, N. (2009). “Some critical episodes in the progress of medical innovation: An Anglo-American perspective”. Research Policy 3 (2), 234–242.
Rosenberg, N., Nelson, R.R. (1994). “American universities and technical advance in industry”. Research Policy 23 (3), 323–348.
Rosenberg, N., Trajtenberg, M. (2004). “A general-purpose technology at work: The Corliss steam engine in the late-nineteenth-century United States”. Journal of Economic History 64, 61–99.
Rosenbloom, R.S., Cusumano, M.A. (1987). “Technological pioneering and competitive advantage: The birth of the VCR industry”. California Management Review 29 (4), 51–76.
Rumelt, R. (1991). “How much does industry matter?” Strategic Management Journal 12, 167–185.
Ruttan, V.W. (1997). “Induced innovation, evolutionary theory and path dependence: Sources of technical change”. Economic Journal 107 (444), 1520–1529.
Sahal, D. (1981). Patterns of Technological Innovation. Addison-Wesley, New York, NY.
Sahal, D. (1985). “Technological guideposts and innovation avenues”. Research Policy 14 (2), 61–82.
Salter, W. (1962). Productivity and Technical Change. Cambridge University Press, Cambridge.
Saviotti, P.P. (1996). Technological Evolution, Variety and the Economy. Edward Elgar Publishing, Cheltenham, UK.
Saviotti, P.P., Trickett, A. (1992). “The evolution of helicopter technology, 1940–1986”. Economics of Innovation and New Technology 2, 111–130.
Saviotti, P.P., Pyka A. (2008a). “Micro and macro dynamics: Industry life cycles, inter-sector coordination and aggregate growth”. Journal of Evolutionary Economics, 18 (2), 167–182.
Saviotti P.P., Pyka A. (2008b). “Product variety, competition and economic growth”. Journal of Evolutionary Economics, 18 (3–4), 323–347.
Schmookler, J. (1966). Invention and Economic Growth. Harvard University Press, Cambridge, MA.
Schumpeter, J.A. (1911). The Theory of Economic Development. Harvard University Press, Cambridge, MA, English Edition, 1934.
Schumpeter, J.A. (1942). Capitalism, Socialism and Democracy. Harper, New York, NY.
Silverberg, G. (1988). “Modelling economic dynamics and technical change: Mathematical approaches to self-organisation and evolution”. In: Dosi, G., Freeman, C., Nelson, R., Silverberg, G., Soete, L. (Eds.), Technical Change and Economic Theory. Pinter Publishing, London, pp. 531–559.
Silverberg, G. (2003). “Breaking the waves: A Poisson regression approach to Schumpeterian clustering of basic innovations”. Cambridge Journal of Economics 27 (5), 671.
Silverberg, G., Lehnert, D. (1993). “Long waves and ‘evolutionary chaos’ in a simple Schumpeterian model of embodied technical change”. Structural Change and Economic Dynamics 4 (1), 9–37.
Silverberg, G., Lehnert, D. (1994). “Growth fluctuation in an evolutionary model of creative destruction”. In: Silverberg, G., Soete, L. (Eds.), The Economics of Growth and Technical Change. Edward Elgar Publishing, Aldershot.
Silverberg, G., Verspagen, B. (1994). “Learning, innovation and economic growth: A long-run model of industrial dynamics”. Industrial and Corporate Change 3, 199–223.
Silverberg, G., Verspagen, B. (1996). “From the artificial to the endogenous: Modelling evolutionary adaptation and economic growth”. In: Helmstadter, E., Perlman, M. (Eds.), Behavioral Norms, Technological Progress and Economic Dynamics: Studies in Schumpeterian Economics. University of Michigan Press, Ann Arbor, MI, pp. 331–371.

Silverberg, G., Verspagen, B. (2005a). “A percolation model of innovation in complex technology spaces”. Journal of Economic Dynamics and Control 29, 225–244.
Silverberg, G., Verspagen, B. (2005b). “Evolutionary theorizing on economic growth”. In: Dopfer, K. (Ed.), The Evolutionary Principles of Economics. Cambridge University Press, Cambridge.
Silverberg, G., Dosi, G., Orsenigo, L. (1988). “Innovation, diversity and diffusion: A self-organising model”. Economic Journal 98 (393), 1032–1054.
Simon, H. (1957). Administrative Behavior (second ed.). Macmillan, New York, NY.
Simon, H. (1962). “The architecture of complexity”. Proceedings of the American Philosophical Society 106 (6), 467–482.
Smith, A. (1776). An Inquiry into the Nature and Causes of the Wealth of Nations. Liberty Fund, Indianapolis, IN Reprinted in 1981.
Soete, L. (1979). “Firm size and inventive activity: The evidence reconsidered”. European Economic Review 12 (4), 319–340.
Soete, L., Turner, R. (1984). “Technology diffusion and the rate of technical change”. Economic Journal 94 (75), 612–623.
Srholec, M., Verspagen, B. (2008). The Voyage of the Beagle in innovation systems land. Explorations on sectors, innovation, heterogeneity and selection. Working Paper No. 2008-008, UNU-Merit, Maastricht.
Stadler, B.M., Stadler, P.F., Wagner, G.P., Fontana, W. (2001). “The topology of the possible: Formal spaces underlying patterns of evolutionary change”. Journal of Theoretical Biology 213, 241–274.
Stanley, M. H. R., Buldyrev, S.V., Havlin, S., Mantegna, R., Salinger, M.A., Stanley, H.E. (1996). “Zipf plots and the size distribution of firms”. Economics Letters 49, 453–457.
Starbuck, W., Mezias, J.M. (1996). “Opening Pandora’s Box: Studying the accuracy of managers’ perceptions”. Journal of Organizational Behavior 17 (2), 99–117.
Steindl, J. (1965). Random processes and the growth of firms. Griffin, London.
Stiglitz, J. (1994). Whither Socialism? MIT Press, Cambridge, MA.
Stoneman, P. (Ed.) (1995). Handbook on the Economics of Innovation and Technical Change. Blackwell Publishing, Oxford.
Stoneman, P. (2007). “Technological diffusion: aspects of self-propagation as a neo-Schumpeterian characteristic”. In: Hanush, A., Pyka, A. (Eds.), Elgar Companion to Neo-Schumpeterian Economics. Edward Elgar Publishing, Cheltenham, UK.
Suarez, F.F., Utterback, J.M. (1995). “Dominant designs and the survival of firms”. Strategic Management Journal 16, 415–430.
Sutton, J. (1997). “Gibrat’s legacy”. Journal of Economic Literature 35 (1), 40–59.
Sutton, J. (1998). Technology and Market Structure: Theory and Evidence. MIT Press, Cambridge, MA.
Svennilson, I. (1954). Growth and Stagnation in the European Economy. UN Economic Commission for Europe, Geneva.
Syverson, C. (2004). “Product substitutability and productivity dispersion”. Review of Economics and Statistics 86 (2), 534–550.
Teece, D. (1986). “Profiting from technological innovation: Implications for integration, collaboration, licensing and public policy”. Research Policy 15 (6), 285–305.
Teece, D., Rumelt, R., Dosi, G., Winter, S.G. (1994). “Understanding corporate coherence: Theory and evidence”. Journal of Economic Behavior & Organization 23, 1–30.
Teece, D., Pisano, G., Shuen, A. (1997). “Dynamic capabilities and strategic management”. Strategic Management Journal 18 (7), 509–533.
Tesfatsion, L., Judd, K. (Eds.), (2006). Handbook of Computational Economics, vol. 2: Agent-Based Computational Economics. North-Holland, Amsterdam.
Tushman, M.L., Anderson, P. (1986). “Technological discontinuities and organizational environments”. Administrative Science Quarterly 31, 439–465.
Utterback, J.M., Suarez, F.F. (1993). “Innovation, competition, and industry structure”. Research Policy 22 (1), 1–21.
Verspagen, B. (1993). Uneven Growth Between Interdependent Economies: A Evolutionary View on Technology Gaps, Trade and Growth. Ashgate, Aldershot.
Vincenti, W. (1990). What Engineers Know and How They Know It. Johns Hopkins University Press, Baltimore, MD.
Von Hippel, E. (2005). Democratizing innovation. MIT Press, Cambridge, MA.
Von Tunzelmann, G.N. (1995). Technology and Industrial Progress: The Foundations of Economic Growth. Edward Elgar Publishing, Cheltenham, UK.
Walsh, V. (1984). “Invention and innovation in the chemical industry: Demand pull or discovery push”. Research Policy 13, 211–234.
Weisbuch, G., Kirman, A., Herreiner, D. (2000). “Market organization and trading relationships”. Economic Journal 110, 411–436.

Winter, S.G. (1971). "Satisficing, selection and the innovative remnant". Quarterly Journal of Economics 85 (2), 237–261.

Winter, S.G. (1982). "An essay on the theory of production". In: Hymans, S.H. (Ed.), Economics and the World Around It. University of Michigan Press, Ann Arbor, MI.

Winter, S.G. (1984). "Schumpeterian competition in alternative technological regimes". Journal of Economic Behavior & Organization 5, 287–320.

Winter, S.G. (1987). "Knowledge and competence as strategic assets". In: Teece, D.J. (Ed.), The Competitive Challenge: Strategies for Industrial Innovation and Renewal. Ballinger Publishing, Cambridge, MA, pp. 159–184.

Winter, S.G. (1993). "Patents and welfare in an evolutionary model". Industrial and Corporate Change 2, 211–231.

Winter, S.G. (2003). "Understanding dynamic capabilities". Strategic Management Journal 24 (10), 991–995.

Winter, S.G. (2005). "Towards an evolutionary theory of production". In: Dopfer, K. (Ed.), The Evolutionary Foundations of Economics. Cambridge University Press, Cambridge, pp. 223–224.

Winter, S.G. (2006a). "Toward a neo-Schumpeterian theory of the firm". Industrial and Corporate Change 15 (1), 125–141 (Original Working Paper, 1968).

Winter, S.G. (2006b). "The logic of appropriability: From Schumpeter to Arrow to Teece". Research Policy 35 (8), 1100–1106.

Winter, S.G. (2008). "Scaling heuristics shape technology! Should economic theory take notice?" Industrial and Corporate Change 17 (3), 513–531.

Winter, S.G., Szulanski, G. (2001). "Replication as strategy". Organization Science 12, 730–743.

Winter, S.G., Szulanski, G. (2002). "Replication of organizational routines: Conceptualizing the exploitation of knowledge assets". In: Choo, C.W., Bontis, N. (Eds.), The Strategic Management of Intellectual Capital and Organizational Knowledge. Oxford University Press, Oxford.

Winter, S., Kaniovski, Y., Dosi, G. (2000). "Modeling industrial dynamics with innovative entrants". Structural Change and Economic Dynamics 11 (3), 255–293.

Winter, S., Kaniovski, Y., Dosi, G. (2003). "A baseline model of industry evolution". Journal of Evolutionary Economics 13 (4), 355–383.

Wright, T.P. (1936). "Factors affecting the costs of airplanes". Journal of Aeronautical Sciences 10, 302–328.

Wright, G. (1997). "Towards a more historical approach to technological change". Economic Journal 107 (444), 1560–1566.

Yelle, L.E. (1979). "The learning curve: Historical review and comprehensive survey". Decision Sciences 10, 302–308.

Yildizoglu, M. (2002). "Competing R&D strategies in an evolutionary industry model". Computational Economics 19 (1), 51–65.

Zheng, L. (2008). System-on-Chip Applications, Lecture Notes—Electronics, Computer and Software Systems. Royal Institute of Technology (KTH), Stockholm.

Ziman, J.M. (Ed.), (2000). Technological Innovation as an Evolutionary Process. Cambridge University Press, Cambridge.