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An introduction to evolutionary theories in economics*

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Abstract. This paper presents the basic ideas and methodologies of a set of contemporary contributions which are grouped under the general heading of "evolutionary economics". Some achievements – especially with regard to the analysis of technological change and economic dynamics – are illustrated, some unresolved issues are discussed and a few promising topics of research are flagged.

Key words: Evolutionary economics – Technological change – Economic change

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1. Introduction

There are signs that evolutionary analysis and models may be making a comeback in economics. Just over the last decade, the book by Nelson and Winter (1982) has been followed by several other works also exploring evolutionary theory in economics (among others, Dosi et al. (1988), Saviotti and Metcalfe (1991), Anderson, Arrow and Pines (1989), Day and Eliasson (1986), Winter (1984) and (1987), Witt (1992), DeBresson (1988), Langlois and Everett (1992), Metcalfe (1992), Stiglitz (1992). This new *Journal of Evolutionary Economics* has been founded and several other new ones have advertised their interest in evolutionary analyses. In fact, evolutionary arguments are not at all new in economics. They go back at least to Malthus[1] and Marx and appear also among economists who have otherwise

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[1] For a recent reappraisal of Malthus as an "evolutionary economist", cf. von Tunzelmann (1991).

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contributed to equilibrium theories: for example one often cites Alfred Marshall on "the Mecca of economics [lying] in economic biology rather than economic mechanics" (Marshall 1948, p. xiv); and also the "as...if" argument by Milton Friedman (1953) can be considered the most rudimentary use of an evolutionary point of view in order to justify the assumptions of equilibrium and rationality. In addition, of course scholars like Veblen, von Hayek and, even more so, Schumpeter, have anticipated many of the ideas that contemporary evolutionary economists are struggling with.[2]

However, the wave of current evolutionary theorizing is probably fostered by several convergent factors. There is certainly a growing recognition of the difficulties that equilibrium theories which presume perfectly rational agents face in interpreting wide arrays of economic phenomena – ranging from the generation of technological change all the way to the diversity of long-term patterns of growth. But, of course, we know from the history of science that anomalies and falsifications alone are not sufficient to spur alternative theories. In addition, a rich empirical literature, concerning the nature of the processes of innovation and the institutions supporting them, to a good extent inspired by evolutionary ideas, has shown that an evolutionary theoretical perspective can provide useful heuristics for applied research. Not only that: the empirical work has suggested fruitful inductive generalizations and taxonomies from which evolutionary theories can draw behavioral assumptions and "stylized facts."[3] Finally, the development of quite general formal machineries able to account for the properties of dynamical systems displaying various forms of non-linearities increasingly allows rigorous analytical treatments of evolutionary processes.[4] This, together with the possibility of computer implementations of formal *gedankenexperiment* concerning diverse "artificial economies" (Lane 1993a, b), holds the promise of establishing also formally sound bases for evolutionary analyses of economic change.

2. Evolutionary theory: principle characteristics and applications to the social domain

In order to present an evolutionary view of economics, it is obvious that we have to explain what an evolutionary theory is and work out general concepts and variables. For the purpose of this special issue let us first mention that we use the term "evolutionary" to define a class of theories, or models, or arguments, that have the following characteristics.[5] First, their purpose is to explain the movement of something over time, or to explain why that something is what it is at a moment in time in terms of how it got there; that is, the analysis is expressly dynamic. Second, the explanation involves both random elements which generate or renew some variation in the variables in question, and mechanisms that systematically winnow on extant variation. Evolutionary models in the social domain involve some

[2] For discussions of the role of evolutionary ideas in the history of economic thought, see Hodgson (1993) and Clark and Juma (1988).
[3] On the economics of innovation, cf. Freeman (1982) and Dosi (1988).
[4] More detailed surveys and discussions of economic applications are in Silverberg (1988) and Dosi and Kaniovski (1994). For a general appraisal, Nicolis and Prigogine (1989), and for economic applications, Rosser (1991).
[5] For a thorough discussion of this point we refer to Nelson and Winter (1982) and Dosi et al. (1988).

processes of imperfect (mistake-ridden) *learning and discovery*, on the one hand, and some *selection mechanism*, on the other. With respect to the latter an evolutionary theory includes a specification of the determinants of some equivalent of a notion of fitness – implying the identification of a unit of selection and certain mechanisms through which selection operates. Moreover, in analogy with evolutionary biology[6] one is able to identify four more concrete principal building blocks of an evolutionary theory: (i) a fundamental unit of selection (the genes); (ii) a mechanism linking the genotypic level with the entities (the phenotypes) which actually undergo environmental selection; (iii) some processes of interaction, yielding the selection dynamics; and, finally, (iv) some mechanisms generating variations in the population of genotypes and, through that, among phenotypes.

It is quite straightforward that one cannot construct a satisfactory theory of economic evolution simply by way of analogy with the biological model. Still, a reference to these four major building blocks of the biological model might help in illustrating the specificities of evolution in the social domain.

2.1 Units of selection

First, consider the nature of the fundamental unit of selection. In a very intuitive fashion, one may spot quite a few potential candidates to be loose equivalents of the genes in biological theory. For example, technologies, policies, behavioral patterns, cultural traits are obviously influential in determining what the agents embodying them – either individuals or organizations – do. (The "agents" here should impressionistically map into the phenotypic level). And technologies, cultural traits, etc. are also something that can be modified, and improved, from generation to generation, and which has its own rules of transmission. In fact, several scholars have proposed arguments of an evolutionary type in the domains of culture, law, institutional history, science and, of course, economics (for a critical appraisal, see Nelson 1993). We do not have any problem with the attribution of the role of "fundamental unit" to different entities according to the objects under consideration. For example, when one talks about the "ecology of the mind" one refers to the changes of some underlying cognitive structures occurring along the history of interactions with other human beings and the environment of artifacts. Here the "primitives" which the evolutionary process is supposed to structure, modify and select are not genes but plausibly mental categories, representations, rules. In domains nearer to our concerns here, evolutionary processes have often been represented as dynamics in some technology-space and, less often, a space of behaviors or organizational forms (we shall come back to some examples later on). But in all these instances of applications of an evolutionary perspective to social change, a crucial issue – in our view, not yet sufficiently explored – concerns the relationship between the level of the "primitives" (so to speak, the genotypic level) and the behaviors of the units which embody them and upon which selection is supposed to operate. The example of "technological evolution," which we shall consider at some detail, is a good illustration of this point.

It does not always happen that one can say that the economy or the society directly "select" among competing technologies (hence also the models based on this premise should be considered as a first approximation to more complex

[6] Note, here and throughout, that, while using sometimes biological analogies for illustrative convenience, we are not at all claiming any precise isomorphism between biological and economic theories of evolution.

dynamics). Sometimes, societies do directly select on technologies: for example, in many medical technologies it occurs through professional judgments based on the peer review system; somewhat similarly, procurement agencies in military technologies perform as direct selectors among alternative technological systems. However, quite often alternative technologies are incorporated within organizations, typically firms – whose relative competitiveness (i.e., "fitness") is mediated through their behavioral patterns – e.g., their decision rules concerning investment, R&D, pricing, scrapping, diversification, etc.[7] Moreover, one typically observes a multiplicity of selection environments affecting the probability of growth and survival of each organization – first, of all, the product-markets and the market for finance. Indeed, it happens in biology and even more so in social dynamics that the objects of selection are not single elementary traits but structures of much higher dimensions in which they are nested. So, for example, markets choose relatively complex ·products or technological systems, and not individual elements of technological knowledge; and penalize or reward whole organizations and not specific behaviors. Therefore, assuming some underlying space of technology and organizational traits as the appropriate "primitive" dimensions of evolution, one still needs some theory of organizational development in order to relate "evolution" and "selection." This is also a major area of complementarity between evolutionary theories and business economics. Notions like those of "organizational routines" and "competencies" begin to forge that link, but, certainly, an item high on the research agenda is the emergence and evolution of routines themselves.[8]

2.2 *Mechanisms and criteria of selection*

Another obvious building block of evolutionary theories concerns the mechanisms and criteria of selection. It has already been mentioned that "fitness" is likely to be judged on different and possibly conflicting criteria. For example, firms might be rationed to different degrees on the financial markets according to their cash-flow, or their accounting profits, or the expectations that investors hold about future profits; and in the product markets, the opportunities of growth and survival may be determined on the grounds of the relative quality of their products, their prices, after-sale servicing, delivery delays, marketing networks, etc.[9] This multidimensionality of selection criteria clearly demands that evolutionary models of e.g., technological or economic change specify the interactive mechanisms through which selection occurs.

Selection in the social arena and its relationship with some notion of "fitness" immediately confronts the question of the endogeneity of the selection criteria themselves. It has been mentioned earlier that also in natural sciences it is the general case that what is selected – in favor or against – might be determined in

[7] Evolutionary models such as Nelson and Winter (1982), Silverberg et al. (1988), Chiaromonte and Dosi (1991), Metcalfe (1992), all illustrate this complementarity of technological and behavioral features in determining competitiveness, and also, admittedly, the rudimentary nature of some behavioral assumptions.

[8] Some preliminary ideas and models are in Marengo (1992), Dosi and Marengo (1993), Dosi et al. (1993a).

[9] Admittedly, most evolutionary models developed so far in economics are based on relatively simple selection criteria, e.g., profits (Nelson and Winter 1982) or prices and delivery details (Silverberg, Dosi and Orsenigo 1988). However, they should be understood as first approximations to more complex selection dynamics.

some complicated and nonlinear ways by the distribution of actual populations present at a point in time and by their history. However, one might still hold that the selection criteria – that is, the variables ultimately affecting probabilities of survival – remain relatively invariant: for example, the rates of reproduction, or the efficiency in accessing food. On the contrary, this might not be so in many economic and social circumstances.

2.3 Adaptation and variation

The last fundamental building block of evolutionary theories concerns the processes by which agents adapt, learn and at the same time novelties are always produced in the system. We shall argue that, at this level, a natural ingredient is a representation of decisions and actions – of individuals and organizations – which departs in most respects from "rational" neoclassical models. Our basic hypothesis is that agents follow various forms of *rule-guided* behaviors which are *context-specific* and, to some extent, *event-independent* (in the sense that actions might be invariant to fine changes in the information regarding the environment). On the other hand, agents are always capable of experimenting and discovering new rules and, thus, they continue to introduce behavioral novelties into the system. (More in Nelson and Winter 1982, Dosi and Egidi 1991, March and Simon 1993). In order to illustrate these points, it is useful to compare evolutionary and neoclassical behavioral assumptions.

The central presumption in neoclassical theory is that the observed configuration of economic variables can be explained as the result of rational actors – individuals, households, firms, other formal organizations – having made choices that maximize their utility, given the constraints they face, and that they have made no systematic mistakes about that. The question of how these optimal decisions came to be is not a basic part of the theory. Sometimes the theory is rationalized in terms of the actors actually having correctly thought through the decision context. Sometimes the rationalization is that the optimal response has been learned or has evolved rather than having been in some sense precalculated, but in any case can be understood "as if" the actor had actually calculated.

Uncertainty and unfortunate results (from the point of view of the actor) that come about because of bad luck of the draw can be admitted under this theory, under either interpretation. The theory also can handle actor errors that occur because the actor has only limited information about certain key parameters which determine the outcomes of making various decisions, and in effect bets wrong regarding these parameters. However, systematic mistakes associated with ignorance, or wrong headed understanding, of the basic features of the situation are not admitted. The theory "works" by presuming the actors have a basically correct understanding of their actual choices and their consequences, as the theorist models that choice context. It is not a theory that tries to get "inside the actor's head," as does, for example, psychiatric theory. Put another way, the rationality assumed by the theory is objective not subjective.

An associated notion is that of equilibrium. In most economic analyses there are a number of actors. Each is assumed to optimize, and the optimization decisions are presumed to be consistent with each other, in that each actor's action is optimizing in the sense above, given the other actor's optimizing actions.

This basic mode of explaining behavior, including the making of predictions about how various possible developments might change behavior, has been employed regarding a vast range of human and organizational action, from analyses of the effects of the oil price shocks of the 1970s, to analyses of the effects of the presence of the death penalty upon crime.

There are several different (but not inconsistent) kinds of reasons why evolutionary theorists have backed away from rational choice theory, and adopted a quite different alternative. First, it can be argued that while rational choice theory provides useful insights into certain kinds of situations and phenomena, it sheds only limited light on others. An important motivation for evolutionary theorizing about, for example, technological advance is that most authors in this field believe that the canons of rational choice theory provide only limited guidance for study of that subject. Second, in many cases models possess multiple equilibria. In each, one can specify the optimizing choice, but behavior and achievement differ greatly across the possible equilibria. A key question then is why the particular equilibrium turned out to be the operative one, and one way of trying to answer this question is to appeal to evolutionary arguments. Third, in any case rational choice theory provides an explanation for behavior that takes the actor's objectives and constraints as given. One can argue that an explanation that considers how social values and institutions have evolved and affect the choices presently available to actors may provide a deeper and more illuminating understanding of behavior than a rational choice explanation alone, even if the latter can explain at one level.

Let us first consider the issue of the limits of the plausible domain of rational choice theory. It is important to recognize, precisely because it is usually repressed, that most economists understand very well how dubious, in any complex context, is the rationale for rational choice theory that presumes the "actors have correctly thought it all through." Beneath the surface faith that actions "optimize" is an understanding that actors are only "boundedly rational," to use Herbert Simon's term (1986). The other rationalization – that the actors have somehow eliminated behavior that was not up to standard – is the argument most economists really believe. (For a good discussion of this point see Winter 1986).

But when put this way, rational choice theory would seem applicable to contexts to which the actors can be presumed familiar, and evolutionary theoretic arguments can be understood as an attempt to deal with situations where this presumption does not seem applicable. In particular, evolutionary theory can be argued to be needed for analyses of behavior in contexts that involve significant elements of novelty, so that it cannot be presumed that good responses already have been learned, but rather that they are still to be learned.

More generally, evolutionary theory can be viewed as a theory about how society, or the economy, learn: in very special cases learning leads to the convergence to some repertoires of "optimal behaviors"; normally it entails more or less temporary, and highly suboptimal, adaptation to what are perceived to be the prevailing environmental constraints and opportunities, and also a lot of systematic errors, trials, and discoveries.

This line of argument would appear to preserve for neoclassical theory the analysis of decision making in situations that are relatively stable and actions repetitive. However, if one bases rational choice theory on accumulated learning, there are apparent limitations to the explanatory power of the theory even in these cases. In particular, learning processes may be very path dependent. Where they end up may depend to a considerable degree on how they got there. While in the steady state actual behavior may be locally optimal, there might be other behavior patterns that would be locally optimal too, some of these in fact much better from the actor's point of view than the actual behavior. Thus a "rational choice" explanation is, at best, incomplete, because it does not explain how the particular local context which frames choices came to be the point of rest. As we shall see, this point of view is a major motivation for evolutionary modeling of "path dependent" dynamic processes.

What about the argument that competition will force firms either to learn the best way of doing things or go out of business? Cannot one argue that, if competitive forces are very strong, firms that are not as efficient as the best firms may be forced out of business? Perhaps one can. But note that the standard here is defined by the most efficient existing firms, not the efficiency that is theoretically possible. And that benchmark level of efficiency may be determined by the actual learning processes that are operative and how far they have proceeded. Thus analyses that do not deal explicitly with learning paths may provide, at best, a quite limited analysis of prevailing equilibrium.

In addition, in many industries there are strong reasons to doubt that selection pressures are strong enough to drive out all firms that are not as efficient as the leader. Empirical studies show that the distribution of firms in an industry at any time often contains very considerable diversity of productivity and profitability.

Further, many of the actors in the economy are not firms. There are universities, legal systems, labor institutions, etc. And these generally are not subject to sharp selection pressures, at least not of a "market" variety.

From a similar but slightly different angle, the neoclassical way of explaining behavior and action can be faulted not so much for exaggerating the power of human and organizational intelligence – as argued above most economists believe the theoretical case for "rational choice" is experiential learning not calculating capabilities – but not for recognizing the extent to which learned behaviors are guided and constrained by socially held and enforced values, norms, beliefs, customs, and generally accepted practices. This argument joins with the one above in proposing that to understand behavior one must come to grips with the forces that have molded it, and in rejecting that such analysis can be short cut by a simple argument that, however learning happened, the ultimate result can be predicted and explained as optimizing behavior.

Conversely, evolutionary theories in economics comfortably match those analyses from social psychology, sociology, organization theory, suggesting the general occurrence of various rule-guided behaviors, often taking the form of relatively invariant *routines* (Nelson and Winter 1982), whose origin is shaped by the learning history of the agents, their pre-existing knowledge and, most likely, also their value systems and their prejudices.[10] Precisely because there is nothing which guarantees, in general, the optimality of these routines, notional opportunities for the discovery of "better" ones are always present. Hence, also the permanent scope for search and novelty (i.e., in the biological analogy, "mutations"). Putting it another way, the behavioral foundations of evolutionary theories rest on learning processes involving *imperfect adaption and mistake-ridden discoveries*. This applies equally to the domains of technologies, behaviors and organizational setups.

With these considerations in mind on the basic "building blocks" of evolutionary theories, let us turn to some applications to technological and economic dynamics.

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[10] On these points, see also Winter (1986) and (1987), Dosi and Egidi (1991), Dosi and Marengo (1993).

3. Technological and economic change: some examples of evolutionary dynamics

3.1 Technical and organizational change

A number of analysts have proposed that technology evolve. The analyses of Freeman (1982), Rosenberg (1976, 1982), Basalla (1988), Mokyr (1990), Nelson and Winter (1977), Dosi (1982, 1984) and Vincenti (1990) are strikingly similar in many respects. (A survey is in Dosi 1988). As an illustration let us consider the discussión of Vincenti.

In Vincenti's theory, the community of technologists at any time faces a number of problems, challenges, and opportunities. He draws most of his examples from aircraft technology. Thus, in the late 1920s and early 1930s, aircraft designers knew well that the standard pattern of hooking wheels to fuselage or wings could be improved upon, given the higher speeds planes were now capable of, with the new body and wing designs and more powerful engines that had come into existence. They were aware of several different possibilities for incorporating wheels into a more streamlined design. Vincenti argues that trials of these different alternatives were somewhat blind. It turned out that having the wheel be retractable solved the problem better than did the other alternatives explored at that time. Thus, search and learning lead to what *ex-post* may be considered as differential "fitness". The latter here is defined in terms of solving particular technological problems better.

But, identification of this criterion also pushes the analytical problem back a stage. What determines whether one solution is better than another? At times, Vincenti writes as if the criterion were innate in the technological problem, or determined by consensus of a technological community who are cooperatively involved in advancing the art.

However, Vincenti also recognizes, explicitly, that the aircraft designers are largely employed in a number of competing aircraft companies, where profitability may be affected by the relative quality and cost of the aircraft designs they are employing, comparing with those employed by their competitors. But then what is better or worse in a problem solution is determined at least partially by the "market," the properties of an aircraft customers are willing to pay for, the costs associated with different designs solutions, the strategies of the suppliers, the changes in the requirements of the buyers, etc.[11]

As already mentioned in the previous section, the link between evolution in the space of technological characteristics and market dynamics rests to a great extent on the organizational and behavioral traits of firms, which in much of evolutionary literature is approximated with *routines*. More specifically, Nelson and Winter (1982) distinguish between three different kinds of routines.

First, there are those that might be called "standard operating procedures," those that determine and define how and how much a firm produces under various circumstances, given its capital stock and other constraints on its actions that are fixed in the short run. Second, there are routines that determine the investment behavior of the firm, and more generally the behaviors which affect its growth or decline (measured in terms of its capital stock) as a function of its profits, and perhaps other variables. Third, the deliberative processes of the firm, those that

[11] This co-evolutionary argument regarding technologies and organizations is prominently illustrated in the work by Alfred Chandler (1962, 1990). A reappraisal of Chandler's contribution in the light of contemporary theories of the firm' is in Teece (1993).

involve searching for better ways of doing things, also are viewed as guided by routines.

The concept of a technological paradigm (Dosi 1982, 1988; Nelson and Winter 1977, 1982) attempts to capture both the nature of the technological knowledge upon which innovative activities draw and the organizational procedures for the search and exploitation of the innovations. First, it refers to the set of understandings about particular technologies that are shared by firms and engineering communities about its present and innate limitations. Second, and relatedly, it embodies the prevailing views and heuristics on "how to make things better." And, third, it is often associated with shared ideas of "artifacts" which are there to be improved in their performances and made cheaper in their production.

We have used the term *technological trajectory* to refer to the path of improvement taken by that technology, given technologists' perceptions of opportunities, and the market and other evaluation mechanisms that determined what kinds of improvements would be profitable. (Sahal 1981 employs analogous concepts.) Note also that the fundamental dimensions of the trajectory in the appropriate technology space are analogous to the "fitness criteria" discussed earlier. By the *technological regime* we mean the complex of firms, professional disciplines and societies, university training and research programs, and legal and regulatory structures that support and constrain development within a regime and along particular trajectories.

3.2 Evolutionary models of growth fuelled by technical advance

Let us now consider a set of models of economic growth in which technical advance is the driving force, and within which technologies and industrial structures co-evolve. The outcomes of this processes are aggregate phenomena such as the growth of labor productivity and per capita incomes, relatively regular patterns of innovation diffusion, persistent fluctuations in the rates of income growth, a secular increase in capital intensities, and other "stylized facts" which traditionally pertain to the economics of growth and development (no single evolutionary model is able alone to account for all these regularities at the same time, but the degree of consistency between the different models focussing on subsets of them is quite remarkable).

Virtually all serious scholars of technical advance have stressed the uncertainty, the differences of opinion among experts, the surprises that mark the process. Mechanical analogies involving moving competitive equilibria in which the actors always behave "as if" the scene were familiar to them seem quite inappropriate. Most scholars agree that the process must be understood as an evolutionary one, in the sense sketched earlier.

The problem addressed by the authors considered in this section has been to devise a theory of growth capable of explaining the observed macroeconomic patterns, but on the basis of an evolutionary theory of technical change rather than one that presumes continuing neoclassical equilibrium.

It would seem inevitable that, in any such theory, firms would be key actors, both in the making of the investments needed to develop new technologies and bring them into practice, and in the use of technologies to produce goods and services. Indeed it is not hard to tell a quite compelling story about economic growth based on firms who compete with each other largely through the technologies they introduce and employ. Joseph Schumpeter laid out that analysis over fifty years ago, and modern analyses largely build upon his conjectures.

Let us concentrate on the first formalized evolutionary model of growth, microfounded into an explicit process of search and competition among heterogeneous actors (Nelson and Winter 1974 and the developments in 1982).

The central actors in this model are business firms. Firms are, from one point of view, the entities that are more or less "fit," in this case more or less profitable. But, from another point of view, firms can be regarded as merely the carriers of "technologies," in the form of particular practices or capabilities that determine "what they do" and "how productively" in particular circumstances. While in principle, within the model, search behaviors could be focussed on any one of the firms' prevailing routines described earlier, – its technologies, or other standard operating procedures, its investment rules, or even its prevailing search procedures – in practice, in all of the Nelson–Winter models, search is assumed to uncover new production techniques or to improve prevailing ones. It is therefore convenient to call such search R&D. Other authors of similar models have invoked the term "learning" to describe analogous improvement processes.

Firms search processes both provide the source of differential fitness – firms whose R&D turn up more profitable processes of production or products will grow relative to their competitors – and also tend to bind them together as a community. In the models in question a firm's R&D partly is focussed on innovating, coming up with something better than what its competitors are doing. But its R&D activities also attend to what its competitors are doing, and profitable innovations are, with a lag, imitated by other firms in the industry.

The firm, or rather the collection of firms in the industry, perhaps involving new firms coming into the industry and old ones exiting, is viewed as operating within an exogenously determined environment. The profitability of any firm is determined by what it is doing, and what its competitors do. Generally the environment can be interpreted as a "market," or set of markets.

The logic of the model defines a dynamic stochastic system. It can be modeled as a complex Markov process. A standard iteration can be described as follows. At the existing moment of time all firms can be characterized by their capital stocks and prevailing routines. Decision rules keyed to market conditions look to those conditions' "last period." Inputs employed and outputs produced by all firms then are determined. The market then determines prices. Given the technology and other routines used by each firm, each firm's profitability then is determined, and the investment rule then determines how much each firm expands or contracts. Search routines focus on one or another aspect of the firm's behavior and capabilities, and (stochastically) come up with proposed modifications which may or may not be adopted. The system is now ready for the next period's iteration.

The model described above can be evaluated on a number of different counts. One is whether the view of behavior it contains, in abstract form, is appealing given the context it purports to analyse. The individuals and organizations in the model act, as humans do in the models of most other social disciplines except economics, on the basis of habits or customs or beliefs; in the Nelson–Winter model all these define routines. There certainly is no presumption, as there is in neoclassical theory, that what they do is "optimal" in any way, save that metaphorically the actors do the best they know how to do. Some scholars, while recognizing a need to pull away from neoclassical canons, might argue that the model sees humans and human organizations as far less "rational" than they are. Indeed, it is quite possible to build more foresight into the actors of an evolutionary theory (see also below). Of course, if one wants a model in which it is presumed that the actors fully understand the context, one might as well use a rational choice model. But then the formidable challenge facing the "rational" models, let alone a supposedly "rational" actors is what it means to "fully understand" the context, whenever the latter depends in some complex, nonlinear ways on the distribution of microdecisions, and on chance, and is always full of surprises.

The model can be judged by the appeal of the theory of technical progress built into it. The view is certainly "evolutionary," and in that regard squares well with the accounts given by scholars of technical advance like Vincenti. However, it contains two "economist" kinds of presumptions. One is that profitability determines the "fitness" of a technology. The other is the central role played by "firms". In any case, the central purpose of this type of models is to explain economic growth at a macroeconomic level. Thus, a fundamental question about them is this: Can they generate, hence in a sense explain, e.g., the rising output per worker, growing capital intensity, rising real wages, and a relatively constant rate of return on capital, that have been the standard pattern in advanced industrial nations? The answer is that they can, and in ways that make analytic sense.

Within Nelson–Winter models a successful technological innovation generates profits for the firm making it, and leads to capital formation and growth of the firm. Firm growth generally is sufficient to outweigh any decline in employment per unit of output associated with productivity growth, and hence results in an increase in the demand for labor, which pulls up the real wage rate. This latter consequence means that capital using but labor saving innovations now become more profitable, and when by chance they appear as a result of a "search," they will be adopted, thus pulling up the level of capital intensity in the economy. At the same time that labor productivity, real wages, and capital intensity are rising, the same mechanisms hold down the rate of return on capital. If the profit rate rises, say because of the creation of especially productive new technology, the high profits will induce an investment boom, which will pull up wages, and drive capital returns back down.

At the same time that the model generates "macro" time series that resemble the actual data, beneath the aggregate at any time there is considerable variation among firms in the technologies they are using, their productivity, and their profitability. Within this simple model (which represses differences in other aspects of firm capabilities and behavior), the technologies employed by firms uniquely determine their relative performance. And within this model more productive and profitable techniques tend to replace less productive ones, through two mechanisms. Firms using more profitable technologies grow. And more profitable technologies tend to be imitated and adopted by firms who had been using less profitable ones.

Soete and Turner (1984), Metcalfe (1988, 1992), Silverberg (1987) and Metcalfe and Gibbons (1989) have developed sophisticated variants on this theme. These authors repress the stochastic element in the introduction of new technologies that was prominent in the model described above and, in effect, work with a given set of technologies. However, within these models each of the individual technologies may be improving over time, possibly at different rates. At the same time, firms are tending to allocate their investment portfolios more heavily towards the more profitable technologies than towards the less. As a result, productivity in the industry as a whole, and measured aggregated "technical advance," is the consequence of two different kinds of forces. One is the improvement of the individual technologies. The other is the expansion of use of the more productive technologies relative to the less productive ones.

Both groups of authors point out that the latter phenomenon is likely to be a more potent source of productivity growth when there is large variation in the productivity across technologies in wide use, than when the best technology already dominates in use. Thus the aggregate growth performance of the economy is strongly related to the prevailing sources of variation across technologies and their levels of diffusion, beneath the aggregate.

The model of Silverberg et al. (1988) develops the basic notions of evolutionary theory in another direction. In that model there are only two technologies. One is potentially better than the other, but that potential will not be achieved unless effort is put into improving current practice. Rather than incorporating a separate "search" activity, in Silverberg et al. a firm improves its prevailing procedures (technologies) through learning associated with operation. What a firm learns is reflected in its increased productivity in using that technology, but some of the learning "leaks out" and enables others using that technology to improve their productivity for free, as it were.

In contrast with Nelson–Winter models where firms do not "look forward" to anticipate future developments, in the model considered here firms, or at least some of them, recognize that the technology that initially is behind in productivity is potentially the better technology, and also that they can gain advantage over their competitors if they invest in using and learning with it. Also in contrast with Nelson–Winter models, a firm may employ some of both technologies, and hence may use some of its profits from using the prevailing best technology to invest in experience with presently inferior technology that is potentially the best. If no firms does this, then of course the potential of the potentially better technology never will be realized.

An early "innovator" may come out a winner, if it learns rapidly, and little of its learning "spills out," or its competitors are sluggish in getting into the new technology themselves. On the other hand, it may come out a loser, if its learning is slow and hence the cost of operating the new technology remains high, or most of its learning "spills out" and its competitors adopt it in a timely manner, taking advantage for free of the spillover.[12]

3.3 Evolution of industries

A joint account of the analyses focussed on the evolution of technology and those focussed on the history of business organizations also appear to suggest that some "typical" evolutionary patterns often appear at industry level (this does not rule out significant exceptions, and one still does not know enough on when and why other dynamics emerge).[13]

The basic model of the evolution of firms and industrial structures (what is sometimes called the "industry life cycle") goes this way. In the early stages of an industry – say automobiles – firms tend to be small, and entry relatively easy, reflecting the diversity of technologies being employed, and their rapid change. However, as a "dominant design" (or a technological "paradigm") emerges, barriers to entry begin to rise as an established scale and capital needed for competitive

[12] Another difference between Nelson–Winter and Silverberg–Dosi–Orsenigo models is that in the latter who "wins" and who "loses" is determined by a selection process captured by a replicator-type dynamics where market shares change according to the relative values of a vector of characteristics, synthetically called "competitiveness."

[13] Contributions from the field of "organizational ecology" also tackle similar life-cycle phenomena, albeit from a different angle; see Hannan and Freeman (1989) and Hannan and Carroll (1991).

production grows. Also, with the basic technological knowledge, learning becomes cumulative, and incumbent firms are advantaged relative to potential entrants for that reason as well. After a shakeout, industry structure settles down to a collection of established largish firms.

Part of this analysis stems from the work by Abernathy and Utterback (1975), done nearly two decades ago, who argued that with basic product configuration stabilized, R&D tends to shift towards improving production processes. When the market is divided up among a large variety of variants, and new products are appearing all the time, product specific process R&D is not particularly profitable. But with the emergence of a dominant design, the profits from developing better ways of producing it can be considerable.

Opportunities for operating on a large scale raise the profitability of exploiting latent economies of scale. Generally, large scale production is capital intensive, and thus capital intensity rises for this reason, as well as because with the stabilization of product design it is profitable to try to devise ways to mechanize production. Since highly mechanized production is profitable only at large scale of output, growth of mechanization and larger scale production go together for this reason as well.

Abernathy and Utterback argue that these dynamics cause major changes in the organization of firms and of the industry after a dominant design is established, and as the technology matures. Mueller and Tilton (1969) made the same argument about the evolution of industry structure some years before Abernathy and Utterback, based on a somewhat less detailed theory of the evolution of technology. Over the last decade articles by Gort and Klepper (1982), Klepper and Grady (1990), Utterback and Suarez (1992), and a recent analytic survey piece by Klepper (1992), have greatly enriched the analysis. However, it still remains to be seen how general are these "life cycles" patterns of industrial evolution. There are two major unsettled issues here, both linked with the characteristics of the learning processes underlying the "competitive advantages" (or disadvantages) of firms.

A first issue concerns the influence that particular "paradigms" and "regimes," as defined earlier, exert on industrial dynamics. The findings in Pavitt (1984) on the size and principal activities of innovating firms, suggest that significant groups of industrial sectors might not conform to the "life cycle" description, due for example to the specificity and tacitness of the knowledge that individual firms embody and to the absence of strong tendencies toward economies of scale (these groups include, for different reasons, machine-tools, scientific instruments, textile and several others). The potential variety in the evolutionary patterns of industries, interpretable on the grounds of different learning and selection regimes is also corroborated by the simulation exercises in Winter (1984) and Dosi et al. (1993). A second major issue concerns the degrees of disruption induced upon industrial structures by discontinuities in the knowledge base and in the "established ways of doing things" (i.e., discontinuities in the technological trajectories of that industry).

While much of the literature on technology and product cycles stops the narrative after a dominant design has emerged and industry structure stabilizes, there is a number of recent theoretical and empirical studies that ask the question, "What happens to a settled industry structure when a new technology comes along that has the promise of being significantly superior to the old?". Thus transistors and later integrated circuit technology ultimately came to replace vacuum tubes and wired-together circuits. At the present time, biotechnology promises a radically new way to create and produce a wide variety of pharmaceuticals, and industrial and agricultural chemicals. The term "competence destroying technical advance" has been coined by Tushman and Anderson (1986) to characterize such new technologies when the skills needed to deal with them are different than the skills and experience that were relevant to the old technologies they threaten to replace.

A considerable body of empirical work now has grown up which persuasively documents that certain new technologies were competence destroying in the above sense. (See, e.g., Tushman and Anderson 1986, and Henderson and Clark 1990). In such instances, the old established firms have had great difficulty in acquiring the new competencies they needed in order to survive in the new regime. New companies built around the new needed competencies tend to come in and grab a significant share of the new market, or firms who have established the needed competencies in other lines of business where they had been appropriate now shift over to the new area to employ their skills there. The extent to which technological discontinuities are associated with *organizational* discontinuities is yet another topic of research in common between evolutionary analyses of industrial change and business economics.

3.4 Chance and structures: path-dependencies and dynamic increasing returns

The discussion above leads naturally to another cluster of analytic and empirical issues coming up in evolutionary theorizing about long run economic change – path dependency, dynamic increasing returns, and their interaction. Path dependencies are built into all of the models considered above, and dynamic increasing returns into some.

Thus, in all of the models, the particular entities that survive in the long run are influenced by events, to a considerable extent random, that happen early in a model's run. To the extent that firms specialize in particular kinds of technology, what technologies survive is influenced similarly by early random events. In some of the models, "dynamic increasing returns" makes path dependency particularly strong. Thus, in Silverberg et al. (1988), the more a firm uses a technology the better it gets at that technology. More, some of the learning "spills over" to benefit other firms using that particular technology. Thus, the more a technology is used, the better it becomes vis-à-vis its competitors.

But while path dependencies and dynamic increasing returns are built into most of the models we already have considered, this was not the center of attention of the authors. Over the past few years, however, a considerable literature in evolutionary economics has grown, focussed on these topics. The works of Arthur (1988, 1989), Arthur et al. (1987) and David (1985, 1992) are particularly interesting, and probably the best known and noted. The simplest versions of these path-dependent models follow a somewhat different analytical strategy from those discussed in the previous section.[14]

There, firms were considered explicitly. They were the "carriers" of technology, and the technology they used affected their "fitness." In the models considered in this section, firms tend to be repressed, and "technologies" per se are the units of analysis. In the former set of models the behavioral description tends to be quite articulated (obviously involving also a few "inductive" generalizations on behavioral

[14] Here we refer mainly to differences in the modelling philosophy rather than in the formal instruments utilized – e.g., generalized Polya urns vs. ordinary differential equations, etc.: a discussion of the more technical aspects of different formal machineries is in Silverberg (1988), Rosser (1991) and Dosi and Kaniovski (1994).

rules). The latter set, on the contrary, tends to focus on some general system properties while being rather agnostic on behavioral assumptions (see Foray's chapter in Foray and Freeman 1992). The simplest version of the latter model basically works through the assumption that each time one technology is used, or bought (and others not), the probability that it will be used or bought next time increases (and the other probabilities decrease). Under conditions of unbounded increasing returns it can be shown that one of the technologies ultimately drives out all its competitors with probability one. But the winning technology is (a) ex ante unpredictable, and (b) might not be the "potential best" of those that competed.

Before discussing the various mechanisms that are argued to lie behind dynamic increasing returns, let us highlight why these analytic arguments are not simply interesting, but provocative. 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's history, there usually are a number of competing variants. Thus in the early history of automobiles, some models were powered by gasoline-fuelled internal combustion engines, some by steam engines, some by batteries. As we know, gradually gasoline-fuelled engines came to dominate and the other two possibilities were abandoned. The standard explanation for this, and it is a quite plausible one, is that gasoline engines were the superior mode, at that time, and with experience that was found out. The Silverberg–Dosi–Orsenigo model contains a variant of this mechanism. In their analysis a potentially superior new alternative requires some development – learning – before its latent superiority becomes manifest. It can take time before that development occurs and, with bad luck, it even is possible that it never occurs. However, one could argue, on the grounds of that model, that given sufficient heterogeneity among adopters (and thus also in expectations, initial skills, etc.) the potentially better technology is likely to win out, albeit at the cost of many "microeconomic tragedies" (unfulfilled expectations, mistakes that nonetheless produce system-level externalities, death of firms etc.).

In the Arthur and David models, one can see a different explanation for why the internal combustion engine won out. It 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.

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 what Nelson and Winter (1982), Dosi (1988) and others have called cumulative technologies. In a cumulative technology, today's technical advances build from and improve upon the technology that was available at the start of the period, and tomorrow's in turn builds on today's. The cumulative effect is like the technology specific learning in the Silverberg et al. model.

Thus, let us return to the history of automobile engine technology. According to the cumulative technology theory, in the early history of automobiles, 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 bets, some working on internal combustion engines, others on steam engines, still others on electric power. Assume, however, that simply as a matter of chance, a large share of these efforts just happened to focus on one of the variants – 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 options, simply as a matter of chance significantly greater advances were made on internal combustion engines than on the other ones.

But then, at the end of the first period, if there were a rough tie before, gasoline powered engines now are better than steam or electric engines. Cars embodying internal combustion engines will sell better. More inventors thinking about where to allocate their efforts now will be deterred from allocating their attention to steam or electric engines because large advances in these need to be achieved before they would become competitive even with existing internal combustion engines. Thus, there are 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 technology 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 dynamic increasing returns stories that have been put forth. 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 early. The other stresses systems aspects where a particular product has a specialized complementary product or service, whose development lends that variant special advantages. Telephone and computer networks, in which each user is strongly interested in having other users have compatible products, are commonly employed examples of the first case. Video cassette recorders which run cassettes that need to be specially tailored to their particular design, or computers that require compatible programs, are often used examples of the second. Paul David's story (1985) of the reasons why the seemingly inefficient "QWERTY" typewriter keyboard arrangement has persisted so long as a standard involves both its familiarity to experienced typists and the existence of typewriter training programs that teach QWERTY.

As in the QWERTY story, the factors leading to increasing returns often are intertwined, and also linked with the processes involved in the development of cumulative technologies. Thus, to return to our automobile example, people who learned to drive in their parents' or friends' car powered by an internal combustion engine naturally were attracted to gas powered cars when they themselves came to purchase one, since they knew how they worked. At the same time the ascendancy of automobiles powered by gas burning internal combustion 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 indicates that "it did not have to be this way." If the toss of the die early in the history of automobiles had come out another way, we might today have had steam or electric cars. A similar argument recently has been made about the victory of A.C. over D.C. as the "system" for carrying electricity. 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.

On the other hand, other analysts may see the above account as overblown. Steam and battery powered car engines had major limitations then and still do now; gasoline clearly was better. A.C. had major advantages over D.C., and still does. According to this point of view, dynamic increasing returns is an important phenomenon, but it is unlikely that it has greatly influenced which technology won out, in most important cases.

Indeed, the relative importance of unique historical circumstances in determining long-term evolution is likely to remain a lively topic of empirical research and argument over the coming years. This is by no means restricted to technological change. It applies as well to fields like the development of particular institutions, the growth of industries or the dynamics of financial markets.[15]

4. Conclusions

In this paper we have attempted to present some major distinguishing features of evolutionary models in general, and, with more detail, in economics. The examples of applications that we presented are only a small subset of the potential research agenda that one is only beginning to explore both via computer-implemented simulation models and via "reduced form" models that have become increasingly amenable to analytical treatments due to the advance in non-linear dynamics and system theory. And, of course, complementary to the theoretical endeavors there is a rich empirical agenda concerning the identification of the regularities in economic structures and in the process of change which are the natural objects of evolutionary explanations. Particularly promising areas of application of evolutionary models include the nature of learning process; the mechanisms of adaptation, discovery and selection underlying economic growth; the theory of the firm and the dynamics of industrial organization.

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[15] In these other domains see for example Kuran (1991), Kirman (1991), Dosi and Kaniovski (1994).

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