Working Paper

Evolutionary Theories in Economics: Assessment and Prospects

Giovanni Dosi
Richard R. Nelson

WP-93-064
November 1993

IIASA
International Institute for Applied Systems Analysis □ A-2361 Laxenburg □ Austria
Telephone: +43 2236 715210 □ Telex: 079 137 iiasa a □ Telefax: +43 2236 71313

Evolutionary Theories in Economics: Assessment and Prospects

Giovanni Dosi
Richard R. Nelson

WP-93-064
November 1993

IIASA International Institute for Applied Systems Analysis ◻ A-2361 Laxenburg ◻ Austria
Telephone: +43 2236 715210 ◻ Telex: 079 137 iiasa a ◻ Telefax: +43 2236 71313

Evolutionary Theories in Economics: Assessment and Prospects

Giovanni Dosi[1]
Richard R. Nelson[2]

[1] Department of Economics, University of Rome "La Sapienza" and International Institute for Applied Systems Analysis, Laxenburg, Austria

[2] Columbia University and NBER, Stanford

Prepared as a chapter for the book *Market and Organization: The Competitive Firm and its Environment*, edited within an EEC/Tempus Programme by LATAPSES, Nice, France and Iside, Rome

(i) Introduction

In this chapter, we shall present the basic ideas and methodologies of a set of contemporary contributions which we shall group under the general heading of "evolutionary economics" (a more precise definition of what we mean will be given shortly). We shall illustrate some achievements -- especially with regards to the analysis of technological change and economic dynamics --, discuss some unresolved issues, and flag a few promising topics of research.

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, Freeman, Nelson, Silverberg and Soete (1988), Saviotti and Metcalfe (1991), Anderson, Arrow and Pines (1989), Day and Eliasson (1986), Winter (1984) and (1987), Witt (1992), De Bresson (1988), Langlois and Everett (1992), Metcalfe (1992), Stiglitz (1992). A 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 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,

[1] For a recent reappraisal of Malthus as an "evolutionary economist," cf. von Tunzelmann (1992).

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 <u>gedankenexperiment</u> concerning diverse "artificial economies" (Lane (1992)),

---

[2] For discussions of the role of evolutionary ideas in the history of economic thought, see Hodgson (forthcoming) 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 (1993). For a general appraisal, Nicolis and Prigogine (1989), and for economic applications, Rosser (1991).

holds the promise of establishing also formally sound bases for evolutionary analyses of economic change.

(ii) Evolutionary Theory: General Principles

One way to try to define evolutionary theory in general would be to start from biology, where evolutionary theory is best worked out, and explore where one can find close analogies to the variables and concepts of that theory in other areas of inquiry -- in this case economics. However, we think it more fruitful to start with the general, and then examine applications in specific areas -- like biology or economics -- as special cases.

Most scholars interested in this issue -- be they from biology, economics, sociology, or whatever -- would agree that the term "evolutionary" ought to be reserved for theories about dynamic time paths, that is ones that aim to explain how things change over time, or to explain why things are what they are in a manner that places weight on "how they got there." The more controversial question is which of such theories ought to be called evolutionary. Until recently most scholars would have probably ruled out theories that are whole deterministic. There would seem no point in saying that Kepler's laws of planetary motion, together with Newton's gravitational theory that explains them, define an evolutionary system. Neither would it seem useful to regard as evolutionary the execution of a detailed plan for the construction of a building, or any realization of a prespecified blueprint. Similarly, theories of economics change that analyze that process as one of moving competitive equilibrium -- as is the case in neoclassical growth theory -- should not be regarded as an "evolutionary" theory.

Recent advances in the understanding of non-linear (but deterministic) systems have highlighted the richness of the dynamics that they may engender, involving, among other things, the possibility of sudden discontinuities in systems' morphology, sensitive history-dependence of the processes and the unpredictable emergence of "novelties" akin to those traditionally associated with stochastic perturbations.[5] However, we shall cover here only a small portion of non-linear dynamics models. Although evolutionary dynamics generally imply non-linearities, the converse is not true: non-linearities are not sufficient to determine that a system is "evolving."

At the opposite extreme, it does not seem to add anything to call "evolutionary" theories where all of the action is "random," as certain models in economics which purport that within an industry the growth or decline of particular firms is a random variable, possibly related to the size of the firm at any time, but otherwise not analyzable. One can trace through the random processes built into such models and predict the distribution of firms sizes at any time, for example that under certain specifications it will asymptotically become log normal. But there does not seem much intellectual value here in saying that under this model the distribution of firms "evolves." Implicitly, then, our archetype of "evolutionary" models contains both systematic and random elements (or, possibly, "quasi-random," such as in those cases whereby innovation are generated by some complex underlying non-linearities that display stochastic features to a finite observer). For example, in biological evolutionary theory the random elements are generally associated with the generation or preservation of variety in a species and the systematic ones with

[5] The presence of chaotic attractors is a case to the point.

selection pressures, and useful extension of the term evolutionary to other areas would appear to require something analogous.

But then revise the building construction story as follows. Assume that the original home design is a tentative one, because the builder is not exactly sure how to achieve what he wants, and thus the plan initially contains certain elements without any firm commitment to them, indeed that are there partly by chance. As the building gets constructed the builder gets a better idea of what the present plans imply, and where the original design is inadequate, and revises the plan and the path of construction accordingly. Revise the firm growth model as follows. Assume that the firms differ in certain identifiable characteristics, and growth of those with certain ones turns out to be systematically greater than those that lack these. The industry gradually develops a structure in which only firms with these characteristics survive.

Both models now contain both random and systematic elements. Further, in both the systematic ones act in a sense by winnowing on the random ones. In the house design case, design elements turn out to please or displease the builder, and are accepted or rejected accordingly. In the industry evolution case, the "market" or something is selecting a certain number of firms that have certain attributes. A limitation of both stories is that neither is explicit about what it is that seems to give advantage. But both give hope that the analyst might be able to find out. Perhaps it is "cost per square foot" or "nice outlooks" or some combination that explains why the builder revises his design as the information comes in. Perhaps it is production costs or ability to innovate that is determining whether firms thrive or fail.

The analytic structure of these two examples is reminiscent of that of evolutionary theory in biology, without being clones of it. There are random elements in the process that generate or are associated with variation. There are systematic elements which are associated with winnowing or focussing.

The latter example is more conformable with evolutionary theory in biology because it refers to an actual population of things, while the former example does not appear to, at least at first glance. In biology the use of the term evolutionary nowadays is firmly associated with analysis of actual populations of things. An embryo, or a living creature more generally, is described as developing, not evolving. In part this use of language reflects a predilection discussed earlier -- that change "according to a plan" is usually not regarded as evolutionary. However, it is widely recognized that many random occurrences will affect the development of an embryo or a tree. The prejudice against using the term "evolutionary" to describe such biological processes stems from the fact that the term has been preempted for use in describing another class of biological phenomena. However, it is not clear that such prejudice should carry over outside of biology.

Consider our house builder, or an individual learning to play chess, or a firm trying to find a strategy for survival in a competitive industry. Our house builder can be regarded as having in his head a number of plan variants, or perhaps as having one initially in mind but being aware that there are a set of possible changes that might turn out to be desirable. Similarly the chess player or the firm. If firms, persons learning to play chess, or housebuilders, learn from experience and winnow or adapt their plans or strategies or behaviors, is it unreasonable to think of these as evolving? In reflecting on this one might recognize that the learning, or adaptation, can be modeled in terms of a change in the probability distribution of possible actions that entity might take at any time, and the discovery of new ones, coming about as a result of feedback from what has been tried, and the consequences. In fact, these "learning" dynamics may well turn out to have a form similar to those which describe the evolution of populations or the evolutionary changes in the internal structures of phenotypes (Holland et al. (1986), Fontana and Buss (1992)).

Can one regard technology as evolving, or science, or law? One certainly can regard the state of these entities at any time as comprising a set of variants that are actually operative in particular contexts. Thus, different firms maybe producing and trying to sell profitably products of somewhat different designs. Different scientists (or technologists) may be working with different hypotheses regarding what is the best way to understand a particular matter (or design a particular artifact). Thus, technology, or science, or the law for that matter, can be treated as an evolving population of "things."

In very general terms, we use the term "evolutionary" to define a class of theories, or models, or arguments, that have the following characteristics. 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 processes of imperfect (mistake-ridden) <u>learning and discovery</u>, on the one hand, and some <u>selection mechanism</u>, on the other.

The variation in the theory can be associated with an actual variety which exists at any time -- as a distribution of genotypes or phenotypes, or firm policies. Alternately, it may characterize a set of potential values of a variable, only one of which is manifest at any time.

The characterization of systematic winnowing forces must be set up so that one can explain what thrives and what does not in terms of something like relative fitness. The theory should include a specification both of the determinants of "fitness," and of the manner in which relative fitness "selects" in the sense above. This is meant to rule out arguments of the sort that something must be fit in some way simply because it exists. It limits the domain of evolutionary theorizing to subject matter where fitness can be assigned plausible meaning, and where selection mechanisms can be specified in some detail. Of course, this does not exclude at all the possibility that "fitness" criteria themselves change in the course of evolution. Indeed, this happens in biology (such as in those cases which are sometimes referred to as "hyperselection" and "co-evolution") and, even more so, one should expect it to happen in social evolution. However, an evolutionary theory, in order to retain interpretative power, ought to be able to specify at least some general characteristics of the process by which selection mechanisms change over time.

More generally, and more technically, it must be emphasized that the unequivocal identification of the variables upon which selection operates is not sufficient to establish the proposition that the frequency of the "fitter" populations (or characters) monotonically increases as evolution unfolds. In fact, this is shown to apply only under particular restrictions on the mechanisms governing the dynamics, such as continuity and linearity of the function driving the change in relative frequencies (for discussions, cf. Silverberg (1988) and Dosi and Kaniovski (1993)).

Note also that in our definition of evolutionary theories there is nothing which amounts to particular hypotheses on the rates of change (either in the generation of variants or in change of the states which the system explores): that is "evolution" is by no means opposed to "revolution." It is also consistent with abrupt changes and major discontinuities in the structure of the systems under consideration. Neither does it involve specific restrictions on the nature of the stochastic processes driving the generation of novelty. For example, evolutionary models of social and economic change -- unlike biological models -- generally involve purposeful learning procedures by individual agents, whose outcomes can be thereafter replicated and diffused both via environmental selection and via observation and imitation by other agents.[6]

If one can understand the determinants of "fitness", and one observes that certain things survive and others do not, one has at least a beginning of an explanation. However, the latter implies the identification of the <u>unit of selection</u>, and the <u>mechanisms</u> through which selection operates. At this level, as Silverberg (1988) emphasizes, simple reasoning by analogy might not take one very far. In order to highlight some differences as well as similarities across disciplines let us briefly compare evolutionary theories in biology with some instances in social sciences.

[6] Incidentally, note that even in biology the beliefs of no genetic-level learning and "blindness" of mutation have been recently challenged by a few scholars; see Rennie (1993).

(iii) Evolutionary Theories: From Biology to Social Disciplines

Evolutionary theory in biology is in flux, and there is far from full agreement on certain matters among modern biologists, ethnologists, paleontologists, and other scientists concerned with the subject. However, the following sketch possibly captures that part of the generally agreed upon core that is useful to lay out for our purposes in this paper, as well as some of the relevant bones of contention.[7]

The theory is concerned with two actual populations as contrasted with potential ones. One is the population of genotypes, defined as the genetic inheritance of living creatures. The second is the population of phenotypes, defined in terms of a set of variables that happen to be of interest to the analyst, but which include those that influence the "fitness" of each living creature. These might include physical aspects like size, or sight, behavioral patterns like song, or responses to particular contingencies like something that can be eaten and is within reach, or a potential mate, or a member of one's own "group" soliciting help.

Phenotypic characteristics are presumed to be influenced by genotypic ones, but not uniquely determined by them. Modern evolutionary theory recognizes that the development of a living creature from its origins to its phenotypic characteristics at any time can be influenced by the environment it passes through. Modern evolutionary theory also recognizes a variety of learning experiences which shape the behavior of a phenotype, including how it was taught by its mother, whether particular behaviors later in life were rewarded, etc. However, if we hold off for a moment considering evolutionary theory that

[7] The following draws from many sources. A good summary can be found in Durham (1991); see also Elridge and Gould (1972) and Gould (1985).

recognizes "culture" as something that can be transferred across generations, the hallmark of standard biological evolutionary theory is that only the genes, not any acquired characteristics or behavior, get passed on across the generations.

The notion of "generations" is basic to biological evolutionary theory. The phenotypes get born, live, reproduce (at least some of them do), and die (all of them do). On the other hand, the genes get carried over to their offspring, who follow the same generational lifecycle. Thus, the genes provide the continuity of the evolutionary system, with the actual living creatures acting, from one point of view, as their transporters from generation to generation. For species that reproduce this way, bisexuality provides a mechanism whereby new genotypes can be created. Mutations do as well. But the emphasis in most treatments of biological evolutionary theory is on differential reproduction of phenotypes which augments the relative genetic frequency of the more successful reproducers and diminishes that of the less.

In the generally held interpretation of this theory (there are other or more complex interpretations as well), selection operates directly on the phenotypes. It is they, not their genes per se, that are more or less fit. To repeat what was stressed above, phenotypes are not uniquely determined by genotypes. However, the theory assumes a strong enough relationship between genotypes and phenotypes so that systematic selection on phenotypes results in systematic selection on genotypes.

There are several controversial, or at least open, aspects of this theory that are germane to our discussion here. One of them is whether, and if so in what sense, evolution can be understood to "optimize" fitness. Note that this discussion presumes that there are some fitness characteristics that evolution systematically selects on.

Assume for the moment that evolution does systematically select on certain fitness characteristics. From that presumption, a number of evolutionary theorists argue that evolution in fact optimizes, in a particular sense. The concept of an evolutionarily stable strategy (ESS) commonly employed in the literature is general enough to encompass situations where a unique bundle of phenotypical characteristics drives out all others, and ones in which what survives is a mix of different phenotypes. (See, e.g., Maynard Smith, 1982.) The concept of "strategy" in these models is broad enough to encompass any phenotypic characteristic that matters for survival, and the strategies that survive are "optimal" just in the sense that they best other strategies that they encounter in the survival game.

Note that the proposition that evolution "optimizes" in this sense carries absolutely no connotation of species optimality. Nothing at al assures "Pareto optimality." All members of the species might do better if all changed in certain ways. Rather, the optimizing concept is that each individual is designed to assure its greatest possible fitness, given the design of the other individuals and the surrounding environment.

Not all theorists of biological evolution buy into all of this. Some argue that there are sometimes strong forces selecting at the level of the group, rather than at the level of the individual. Later when we consider selection in economic analysis, the question of the nature and strength of mechanisms of selection will be a prominent concern.

For our purpose here, however, let us consider especially the controversy of whether it is plausible to think of evolution as optimizing, either at the individual or group level.

All evolutionary theorists admit that mutation involves major elements of chance. While in biology most mutations diminish fitness or are neutral, some obviously have enhanced it. However, it is apparent that phenotypes need to be understood as systems of genes and associated characteristics which interact in determining fitness. Thus, whether a particular mutation is helpful or neutral or lethal is a function of the rest of the system that mutation modifies in some way. Thus, even if evolution can be regarded as optimizing fitness, the optimum is very local and likely poor stuff compared to what might have been.

An even more fundamental argument is that those that propose evolution optimizes fitness presume a relatively stringent and constant selection environment. But selection pressures often are not particularly severe, or discriminating. Thus the "random" element in evolution lies not just in mutation (and cross breeding) but also in the determination of what survives and what does not, which may have little to do with any basic "fitness" qualities, except for eliminating gross misfits. Further, even when selection pressures are stringent, they generally reflect the particularities of a situation -- the nature of the extant food supply, the predator population, etc. -- which may not be a constant. Thus the distribution of genotypes extant today may be strongly shaped by those that survived in a very different environment some time ago, and the offspring they had, as well as yesterday's winnowing on the group extant then. The notion of ESS is indeed a static concept which neglects any explicit account of the process driving to the purported equilibria (Silverberg (1988)). Moreover, even when embedded into a dynamic process, the notion of ESS rests on the idea that the changes in the factors which influence "fitness" and selection (i.e., changes in the payoff matrix) are much slower than, and independent from, adjustments to any given structure of payoffs.

A related argument focusses on the continuing nature of evolution. To the extent that mutation continues and some of the mutations enhance fitness, what meaning is there to the proposition that what one observes at any time is optimal?

Note the similarity of the arguments here to those we considered earlier, about whether competition assures "optimum" behavior. We shall meet these questions again later.

As indicated, animal behavior has been, for a long time, a "phenotype" characteristic of interest to evolutionary theorists. That behavior often involves, in an essential way, modes of interaction with fellow members of one's species. Over the last thirty years an important subdiscipline has grown up concerned with exactly these kinds of social behavior patterns. Much of this has been concerned with nonprimate animals -- insect colonies, bird families and flocks, etc. A sizeable portion of it has been, however, concerned with humans. The part of the sociobiology literature concerned with nonhumans recognizes that learned behavior can be passed down from generation to generation, but in general has presumed, first, that the particular capabilities to learn and to transmit to offspring are tied to genes, and second, that the "learning" does not not progress from generation to generation. To the extent that these behaviors enhance fitness, there is selection on the genes that facilitate them, according to the arguments sketched above. But learned behavior in these theories does not follow a cross generational path of its own. Conversely, significant amendments to the theory are required whenever one acknowledges explicit mechanisms of intergenerational transmission of learned behaviors -- as it is plausibly the case at least in the socio-economic domain.[8]

Clearly, we are not in a position to argue in favor of a particular biological theory. For our purpose here it suffices to point out that, at least in principle, the theory identifies (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.

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

[8] All the foregoing caveats also apply to literal applications of biological models to economic analysis, including "evolutionary games." It is not the purpose of this work to discuss the latter stream of literature (for a survey, see D. Friedman (1991)). Let us just point out that, in their current format, they generally embody quite restrictive assumptions on the relationship between intrinsic traits (i.e., the metaphorical equivalent of "genes") and "strategies." Moreover, another common assumption is the fixity of the environment determining relative "fitness." Even under these special conditions asymptotic outcomes do not generally guarantee convergence to Pareto-dominant equilibria (and, sometimes, in discrete-time games not even to Nash equilibria at all: cf. Dekel and Scotchmer (1991)). Of course, it is only reasonable to expect these "suboptimal" properties of evolution to carry over to the more general evolutionary setups that we are discussing here.

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, representation, 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 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 incorporate 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.[9] 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 (see also the chapter in this volume

[9] Evolutionary models such as Nelson and Winter (1982), Silverberg, Dosi and Orsenigo (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.

by Dosi and Teece), but, certainly, an item high on the research agenda is the emergence and evolution of routines themselves.[10]

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.[11] 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. It is indeed sad to admit in a book primarily conceived for Eastern European countries undertaking the transition to 'market economies' that in fact one knows very little on how markets actually work and even less of the fundamental differences in the selection dynamics across a variety of them![12]

---

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

[11] 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.

[12] For example, one does not have any good theory of why in most markets economic agents utilize prices and not quantities as their main decision variables, or why observed price dispersions at any moment are what they are. Of course, it is easy to blame this lamentable state of affairs on orthodox economic theory, which, by focusing on the property of equilibria, has made irrelevant the analysis of adjustment processes. For one of the rare observation-based descriptions of a market which raises a lot of challenging

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 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.

Consider as an illustration the metaphor of the "evolutionary house building" from the previous section. One can imagine that the selection criterion is "cost per square foot" or this and also "height" and "resistance to earthquakes." One can easily figure out very complicated evolutionary dynamics on the "landscape" -- as biologists sometimes call it -- defined in these three dimensions. However, it still holds that in some intuitive sense "fitter" stands for "lower cost," "more height," "more resistance." Consider now the case where selection occurs only on the grounds of "nice outlooks" and suppose that people change their tastes along the way by talking to each other, reading art books, visiting other towns living in the house. Here one faces also a basic indeterminacy concerning the very dimensions of the "evolutionary landscape." There is still variation and selection but the theory is unable to specify even ex-post the general variables which have determined why architecture has "evolved" toward brickhouses in one place and neogothic ones in another.

---

theoretical questions, see Kirman (1991). For some general considerations, cf. Okun (1981).

Relatedly, also the interpretative power of the models change: in the latter circumstances they are obviously inapt to make "predictions," and also the "explanation" that they provide might be limited to some invariant characteristics of the process (for example of social imitation, etc.). Only a detailed historical reconstruction may be able to account for the fact that, say, the English ended up eating what the majority of mankind consider atrocious food and the French a sophisticated cuisine.

Probably, in social sciences one encounters different combinations between the two extreme cases. Sometimes, it is rather straightforward to identify the dimensions nesting the process of search for "better metal cutting machines." Other cases, such as the dynamics of financial markets described by John Maynard Keynes with his "beauty contest" metaphor, look more like the second extreme.[13]

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

[13] And so might well be the evolution of cultures, religions, etc.: see Nelson (1993).

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 comes 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 head understanding, of the basic features of the situation, are not admitted. The theory "works" by presuming the actor has 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 in 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 insight 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 of choice situations 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 snuff -- 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 in analysis 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.

As we shall see, this position characterizes economists who have seen economic growth as a process largely driven by continuing technological advance. Virtually all scholars of technological advance highlight the uncertainties, the differences in judgment among experts, and the surprises that are common in the process, which would seem to take it outside the domain of rational choice theory. While the actors involved can be regarded as having certain objectives in mind, as trying their best to analyze what they should do, and as drawing on past experience to gain insight into the present, the actions they take cannot be understood as "optimizing" except in the sense that they represent the actors' best bet regarding what to do. Under these circumstances, the theory of microeconomic adaptation <u>and mutation</u> focusses on the nature of learning processes.

This line of argument would appear to preserve for neoclassical theory 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? Can't one ague that, if competitive forces are very strong, firms that aren't 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.[14] 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 adaptation and mistake-ridden discoveries. This applies equally to the domains of technologies, behaviors and organizational setups. Of course, the "imperfections" of adaptation and the continuous existence of opportunities of "doing better" and "inventing new things" implies that heterogeneity is rarely weeded out by environmental selection. Possible phenomena of historical "lock-in" (which we shall discuss below) are most often disrupted by the emergence of novelties, which under certain circumstances, can "invade" apparently well

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

established system of, e.g., production, corporate organization, consumption, etc.

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

(iv) Technological and Economic Change: Some Examples of Evolutionary Dynamics

Technical and Organizational Change

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

This co-evolutionary argument regarding technologies and organizations is prominently illustrated by Alfred Chandler's research ((1962) and (1990)) on the emergence of the complex structures that characterize modern multi-product firms.[15] He argues that a variety of technological developments occurred during the mid and late 19th century which opened up the possibility for business firms to be highly productive and profitable if they could organize to operate at large scales of output, and with a relatively wide if connected range of products. He describes various organizational innovations that were tried, and while his central focus is on those that "succeeded," it is clear from his account that not all did. Arguing in a manner similar to Vincenti, Chandler's "fitness criterion" is that the new organizational form solved an organizational problem.

[15] A reappraisal of Chandler contribution in the light of contemporary theories of the firm is in Teece (1993).

Presumably the solution to that problem enabled a firm to operate at lower costs, or with greater scale and scope, in either case, with greater profitability. Like Vincenti, Chandler clearly sees a community, in this case of managers. But he also sees companies competing with each other. His argument is that companies which found and adopted efficient managerial styles and structural forms early won out over their competitors who did not, or who lagged in doing so.

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

The concept of a technological paradigm (Dosi (1982) and (1988)), Nelson and Winter ((1977) and (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.

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 (1940) 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 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.

Firm 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.

Note that in the theory that has been sketched above, just as routines are analogous to genes, firms are analogous to phenotypes in biological evolutionary theory, but there are profound differences. First, firms do not have a natural life span, and not all ultimately die. Neither can they be regarded as having a natural size. Some may be big, some small. Thus in assessing the relative importance of a particular routine in the industry mix, or analyzing whether it is expanding or contracting in relative use, it is not sufficient to "count" the firms employing it. One must consider their size, or whether they are growing or contracting. Second, unlike phenotypes that are stuck with their genes, firms are not stuck with their routines. Indeed they have built-in mechanisms for changing them.

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 expanded 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 analyze. 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" actor) 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 a 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 prevailing large variation in the productivity of 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 variation beneath the aggregate.

The model of Silverberg, Dosi, and Orsenigo (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 prevailing 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 firm 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 get in a timely manner, taking advantage for free of the spillover.[16]

A few other evolutionary models of growth have been developed. Gunnar Eliasson has developed a series of phenomenologically rich models which have been "realistically" calibrated on the Swedish economic (cf. Eliasson's chapter in Day and Eliasson (1986)).

---

[16] Another difference between Nelson-Winter models and Silverberg-Dosi-Orsenigo 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."

Chiaromonte and Dosi (1992) merge many of the elements of Nelson-Winter stochastic search for new techniques and Silverberg-Dosi-Orsenigo equipment-related learning in a two-sector evolutionary model. Silverberg and Lenhart (1992) study the time series properties of growth dynamics driven by a Poisson arrival of innovations jointly with a Goodwin-type dynamics of wages and investment. Iwai (1984) and Coulisk (1989) propose other interesting variants of evolutionary models of industrial structures and aggregate growth, respectively.

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).[17]

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" emerges, barriers to entry begin to rise as the scale and capital needed for competitive production grows. Also, with the basic technology 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

[17] 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).

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 changes cause major changes in the organization of firms and 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 of 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 (see also the chapter by Dosi and Teece in this volume).

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 virtually all of the models, the particular firms 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, Dosi, and Orsenigo (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 up focussed on these topics. The works of Brian Arthur (1988, 1989), Arthur, Yuri Ermoliev and Yuri Kaniovski (1987) and Paul 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.[18]

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

[18] 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 (1993).

involving also a few "inductive" generalizations on behavioral 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 lie 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. Alternatively, assume that while the distribution of inventive efforts were relatively even across the three alternatives, simply as a matter of chance significantly greater advances were made internal combustion engines than on the other alternatives.

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 had 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 internal combustion engine pulls even farther 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 further improving it.

There are two 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 role 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 firms or the dynamics of financial markets.[19]

V. Conclusions

In this chapter we have attempted to present the major distinguishing features of evolutionary models in general, and, with much 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 processes of change which are the natural objects of evolutionary explanations. Particularly promising areas of application of evolutionary models include the nature of learning processes; the mechanisms of adaptation, discovery and selection underlying economic growth; the theory of the firm and the dynamics of industrial organization.

[19] In these other domains see for example Kuran (1991), Kirman (1991), Dosi and Kaniovski (1993).

REFERENCES

Abernathy, W. and J. Utterback. (1975) "A Dynamic Model of Process and Product Innovation," Omega, 639-656.

Anderson, P.; K. Arrow and D. Pines. (19888) The Economy as an Evolving Complex System. Redwood City, CA: Addison-Wesley Publishing Co.

Arthur, B., Y. Ermolies and Y. Kaniovski. (1987) "Path Dependent Processes and the Emergence of Macrostructure," European Journal of Operational Research.

Chandler, A. (1962) Strategy and Structure: Chapters in the History of American Industrial Enterprise. Cambridge, MA: Harvard University Press.

Chandler, A. (1990) Scale and Scope: The Dynamics of Industrial Capitalism. Cambridge, MA: Harvard University Press.

Chiaromonte, and G. Dosi. (1992) "The Microfoundations of Competitiveness and Their Macroeconomic Implications," in Foray and Freeman (1992).

Clark, N., and C. Juma. (1988) "Evolutionary Theories in Economic Thought," in Dosi et et al. (1988).

David, P. (1985) "Clio and the Economics of QWERTY," American Economic Review Papers and Proceedings, 75: 332-337.

Day, R. and G. Eliasson (eds.). (1986) The Dynamics of Market Economies, Amsterdam: North-Holland.

De Bresson, C. (1987) "The Evolutionary Paradigm and the Economics of Technological Change," Journal of Economic Issues, 751-761.

Dekel, E. and S. Scotchmer. (1991) "On the Evolution of Optimizing Behavior," Journal of Economic Theory.

Dosi, G. (1982) "Technological Paradigms and Technological Trajectories: A Suggested Interpretation of the Determinants and Directions of Technical Change," Research Policy, 147-162.

Dosi, G. (1988) "Sources, Procedures, and Microeconomic Effects of Innovation," Journal of Economic Literature, 26: 126-171.

Dosi, G., and M. Egidi. (1991) "Substantive and Procedural Uncertainty: An Exploration of Economic Behaviours in Changing Environments," Journal of Evolutionary Economics.

Dosi, G., and Y. Kaniovski. (1993) The Method of Generalized Urn Schemes in The Analysis of Technological and Economic Dynamics. Luxembourg, Austria: IIASA Working Paper 93-17.

Dosi, G., and L. Marengo. (1993) "Toward an Evolutionary Theory of Organizational Competencies," in R.W. England (ed.), Evolutionary Concepts in Contemporary Economics. Ann Arbor, MI: University of Michigan Press, forthcoming.

Dosi, G.; O. Marsili, L. Orsenigo and R. Salvatore. (1993) Learning, Market Selection and the Evolution of Industrial Structures. Berkeley: Center for Research in Management, CCC Working Paper.

Dosi, G., L. Marengo, A. Bassanini and M. Valente. (1993a), The Evolutionary Emergence of Norms. Rome: Department of Economics, and Berkeley, CA: Center for Research in Management, mimeo.

Durham, W. (1991) Co-Evolution: Genes, Culture, and Human Diversity. Stanford, CA: Stanford University Press.

Eldridge, and S. J. Gould. (1972) "Punctuated Equilibria: An Alternative to Phyletic Gradualism," in T.J.M. Schopf (ed.), Models in Paleobiology. San Francisco: Freeman & Co.

Eliasson, G. (1986) "Microheterogeneity of Firms and the Stability of Industrial Growth," in Day and Eliasson (1986).

Fontana, W. and L.W. Buss. (1992) What Would be Conserved if 'the Tape Were Played Twice'?. Santa Fe, NM: SFI mimeo.

Foray, D., and C. Freeman (eds.). (1992) Technology and the Wealth of Nations. London: Francis Pinter.

Freeman, C. (1982) The Economics of Industrial Innovation, London: Francis Pinter, 2nd ed.

Friedman, D. (1991) "Evolutionary Games and Economics," Econometrica, 59, pp. 637-666.

Friedman, M. (1953) Essays in Positive Economics. Chicago: University of Chicago Press.

Gort, M., and S. Klepper. (1982) "Time Paths in the Diffusion of Product Innovations," Economic Journal, 630-653.

Gould, S.J. (1985) The Flamingo's Smile: Reflections in Natural History. New York: Norton.

Hannan, M.T., and G. R. Carroll. (1991) The Dynamics of Organizational Populations. Oxford: Oxford University Press.

Hannan, M., and J. Freeman. (1989) Organizational Ecology. Cambridge, MA: Harvard University Press.

Henderson, R., and K. Clark. (1990) "Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms," Administrative Sciences Quarterly, 9-30.

Hodgson, G. (forthcoming) "Economics and Evolution: Bringing Life Back Into Economics."

Holland, J.H.; K.J. Holyoak, R.E. Nisbett and P.R. Theard. (1986) Induction. Cambridge, MA: MIT Press.

Iwai, K. (1984) "Schumpeterian Dynamics Part I and Part II," Journal of Economic Behavior and Organization, 159-190, 321-351.

Kirman, A. (1991) "Epidemics of Opinion and Speculative Bubbles in Financial Markets," in M. Taylor (ed.), Money and Financial Markets. London: Macmillan.

Kirman, A. and A. Vignes. (1992) "Price Dispersion: Theoretical Considerations and Empirical Evidence from the Marseilles Fish Market," in K. Arrow (ed.), Issues in Contemporary Economics. Vol I.: Markets and Welfare. London: Macmillan.

Kuran, T. (1991) "Cognitive Limitations and Preference Evolution," Journal of Institutional and Theoretical Economics.

Lane, D. (1992) Artificial Worlds and Economics. San Fe, NM: SFI Working Paper 92-08-48.

Langlois, R., and M. Everett. (1992) "What is Evolutionary Economics," University of Connecticut, Storrs, CT: unpublished paper.

March, I. (1992) Exploration and Exploitation. Stanford: Stanford Business School, mimeo.

March, J. and H. Simon. (1993) Organizations. Oxford: Basil Blackwell. 2nd ed.

Marengo, L. (1992) "Coordination and Organizational Learning in the Firm," Journal of Evolutionary Economics.

Marshall, A. (1948) Principles of Economics. London: Macmillan. 5th Edition.

Metcalfe, S. (1988) "The Diffusion of Innovations: An Interpretative Survey," in Technical Advance and Economic Theory, in Dosi et al. (1988). London: Pinter Publishers.

Metcalfe, S. (1992) "Variety, Structure and Change: An Evolutionary Perspective on the Competitive Process," Revue d'Economie Industrielle, 46-61.

Metcalfe, S., and Gibbons. (1989) "Technology, Variety, and Organization," in Research on Technological Innovations, Management and Policy. Vol. 4. JAI Press, pp. 153-193.

Mueller, D., and J. Tilton. (1969) "Research and Development as Barriers to Entry," Canadian Journal of Economics, 570-579.

Nelson, R. (1993) "Evolutionary Theorizing about Economic Change," Stanford: NBER, and New York: Columbia University mimeo.

Nelson, R., and S. Winter. (1974) "Neoclassical Versus Evolutionary Theories of Economic Growth: Critique and Perspective," Economic Journal, 886-905.

Nelson, R., and S. Winter. (1977) "In Search of Useful Theory of Innovation," Research Policy, 36-76.

Nelson, R., and S. Winter. (1977) An Evolutionary Theory of Economic Change. Cambridge, MA: Harvard University Press.

Nicolis, and I. Prigogine. (1989) Exploring Complexity: An Introduction. New York:

Freeman.

Okun, A.M. (1981) Prices and Quantities. Oxford: Basil Blackwell.

Pavitt, K. (1984) "Sectoral Patterns of Innovation: Toward a Taxonomy and a Theory," Research Policy.

Rennie, J. (1993) "DNA's New Twists," Scientific American (March).

Rosser Jr., J.B. (1991) From Catastrophe to Chaos: A General Theory of Economic Discontinuities. Boston,, Dordrecht: Kluwer.

Sahal, D. (1981) Patterns of Technological Innovation. Reading: Addison-Wesley.

Saviotti, P., and J. Metcalfe (eds.). (1991) Evolutionary Theories of Economic and Technological Change. Reading: Harwood Academic Publishers.

Silverberg, G. (1987) "Technical Progress, Capital Accumulation and Effective Demand: A Self-Organization Model," in D. Batten, J. Casti and B. Johansson (eds.), Economics Evolution and Structural Adjustment. Berlin/New York: Springer Verlag.

Silverberg, G. (1988) "Modelling Economic Dynamics and Technical Change: Mathematical Approaches to Self-Organization and Evolution," in Dosi et al. (1988).

Silverberg, G. and D. Lenert. (1992) "Long Waves and evolutionary Chaos' in a Simple Schumpeterian Model of Embodied Technical Change," Masstricht: MERIT working paper.

Silverberg, G.; G. Dosi and L. Orsenigo. (1988) "Innovation, Diversity, and Diffusion: A Self Organizing Model," Economic Journal, 1032-1054.

Soete, L., and R. Turner. (1984) "Technological Diffusion and the Rate of Technical Change," The Economic Journal, 612-623.

Stiglitz, J. (1992) Notes on Evolutionary Economics: Imperfect Capital Markets, Organizational Design and Long Run Efficiency. Stanford: Department of Economics mimeo.

Teece, David J. (1993) "Perspectives on Alfred Chandler's Scale and Scope," Journal of Economic Literature.

von Tunzelmann, N. (1992) "Malthus as an Evolutionary Economist," Journal of Evolutionary Economics.

Tushman, M., and D. Anderson. (1986) "Technological Discontinuities and Organizational Environments," Administrative Sciences Quarterly, 439-465.

Utterback, J., and F. Suarez. (1992) "Innovation, Competition, and Market Structure," Research Policy, 1-21.

Vincenti, W. (1990) What Do Engineers Know and How Do They Know It?. Baltimore: Johns Hopkins Press.

Winter, S. (1984) "Schumpeterian Competition under Alternative Technological Regimes," Journal of Economic Behavior and Organization.

Winter, S. (1986) "The Research Program of the Behavioral Theory of the Firm: Orthodox Critiques and Evolutionary Perspectives," in Handbook of Behavioral Economics, volume A, edited by B. Gilad and S. Kaish. Greenwich, CT: JAI Press.

Winter, S. (1987) "Natural Selection and Evolution," The New Pelgrave. London: Macmillan.

Witt, U. (1992) Evolutionary Economics. London: Edward Elgar.