1. Introduction

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1. INTRODUCTION

The title of this book raises the problem of the appropriateness of the empirical methods used to test and to apply a given theory to the theory itself. Evolutionary economics differentiates itself from the dominant tradition in economics in a number of assumptions, but these different assumptions can be related to two different and not easily compatible world-views. In order to answer the main question of the book it is important to formulate clearly the main differences between evolutionary and neo-classical economics, to relate them to the two underlying world-views, and to find out to what extent such fundamental differences imply different methods of empirical analysis.

1.1 Neo-classical vs Evolutionary Economics

It is to be noted that these two theories are not equivalent since the former is at a very advanced phase of its life cycle while the latter is at a very early phase. Neo-classical economics has been developed over a period of approximately 140 years while the origins of evolutionary economics can be traced back to the beginning of the 1980s. In spite of these different 'ages' of the two theories the main differences between them can be clearly established. First, the concept of equilibrium. In neo-classical economics the economic system is assumed to be generally at equilibrium, and to return to an equilibrium position after a disturbance. In evolutionary economics the phenomena that give rise to true economic development are non-equilibrium phenomena. As Schumpeter (1912, 1934) had so clearly foreseen, the capitalist economic system is restless and its development occurs precisely by destroying given equilibria. The difference between the two theories is more clearly appreciated if we introduce the idea of qualitative change. The economic system of the early twenty-first century is not just a bigger replica of that of the 1930s or of the 1850s, but it contains many different entities which were not present in previous times (Saviotti, 1996). The concept of equilibrium becomes very problematic in the

presence of qualitative change: how can a given system undergo a transition between two different states in which different entities are present while remaining at equilibrium?

Second, evolutionary economics is considered intrinsically more dynamic than neo-classical economics (Nelson, 1995; Dosi and Nelson, 1994). This cannot be interpreted as an absence of dynamics in neo-classical economics: growth models of different vintages contain differential equations in which time is a variable. The true difference is the dynamics of qualitative change that neo-classical economics excludes, while evolutionary economics takes it into account. Third, the heterogeneity of agents is taken into account explicitly by evolutionary economics while neo-classical economics has greater difficulties in coping with it. In fact this difference can be related to two different approaches, a typological and a population-based approach. In the former only the representative elements of a population are taken into account, thus considering only their average values, while in the latter the average values and their distribution within the population are considered important. In a typological approach only the representative firm or customer is considered, while the distribution of properties within the population of firms or customers is not taken into account. These differences between neo-classical and evolutionary economics are not just specific differences between two theories, but they are part of a change in world-view that took place mostly during the twentieth century.

1.2 Two Different World-views

By the mid-nineteenth century the successes of physics had given rise to a world-view that was later to be called the 'Laplacian dream', after Pierre Simon Laplace who, at the beginning of the nineteenth century, attempted to give a systematic mathematical formulation of Newton's theories (Mirowski, 1989; Prigogine and Stengers, 1984, p. 28). In this world-view we had become convinced that we were in principle able to know the physical world. It was thought that both the basic components of the universe and the interactions amongst them were known. It is important to stress that such knowledge, while considered possible in principle, could be difficult to achieve in practice, because computation costs could be very high. The world was also seen as deterministic, reversible and in principle calculable. This world-view has long since been abandoned in physics, though not without traumas in the profession, but it still holds a great place in economics. During the past century our world-view has changed considerably. This is true for our expectations about the knowledge that we can possibly gain of the external world, be it physical or social. An alternative,

even if not yet as complete as the Laplacian dream purported to be during the nineteenth century, is today provided by what can generally be called theories of complexity. It has to be admitted from the start that such theories are by no means unified, except for some extremely broad generalizations. To begin with, our certainty to be able in principle to know the world has been severely dented. First, quantum mechanics pointed out that our knowledge of the physical world was intrinsically limited: observations of an unperturbed physical world were in principle impossible. The knowledge that we could gain of the physical world could at best be statistical. Later theories of non-linear systems and of chaos demonstrated that even a system represented by a deterministic equation could behave in a chaotic and non-reproducible way. If these are difficulties in our understanding of physical reality, even greater difficulties exist in the social sciences. To begin with, the social sciences have to deal with structures of essential complexity (Hayek, 1978, p. 26), that is, structures whose characteristic properties can be exhibited only by models made up by a very large number of variables. The meaning of essential complexity can be better understood in the light of the distinction between organized and unorganized complexity. The phenomena studied by the social sciences are of the former type and, as a consequence, the properties of the entities analysed are due not only to their individual elements but also to their interactions. An additional difficulty for what concerns the social sciences is that knowledge in this area can influence the state of the subset of the external environment that it is studying. In other words, once we create a theory that understands and interprets social reality or a part of it, that same theory can contribute to change the subset of social reality investigated, thus requiring a new theory. In this sense social reality is even more difficult to observe in an unperturbed way than physical reality.

The reasons for the emergence of the Laplacian dream are fairly complex and cannot be given a detailed discussion in this chapter. However, it seems clear that the Laplacian dream was an exaggeration. It extrapolated our capacity to know a limited subset of our external world to all of the external world. Nevertheless, our recognition of the limits of human knowledge is not to say that we know less or can know less than we did a century or two ago. In fact our knowledge of the physical world has immensely increased during the twentieth century. The fact that more scientific publications have been produced during this century alone than in all previous history does not prove the claim. It would in fact be possible for the basic principles of knowledge to have been established previously, and for most of the work done in the twentieth century to have been simply an extension of these basic principles to new situations; or, in other words, an extension of the paradigm embodied in classical mechanics. In

fact, during the twentieth century not only did we accumulate an enormous amount of knowledge about new situations, but our world-view changed to a considerable extent. The emerging world-view is not complete, but it amounts to saying that the world is far more complex than we previously thought and that our potential for knowing it is limited. Uncertainty and complexity are two often recurring words in today's literature. To represent this change we could say that we previously based our claim to be able to know all of physical reality on the results of the study of some simple systems. We now know of some much more complex systems, but we are not sure about the extent to which the laws that can be derived for such systems are applicable to others. Today we see the universe as being much wider than before, but we do not expect to be able to know all of its range. Yet what we know of it might easily be much greater than the initial range. Thus we know a lot more, although the perception we have of our limits has become clearer.

As concerns the social sciences, and economics in particular, the model of knowledge creation and validation was represented by physics. This was not peculiar to the social sciences. Physics was in general considered to be the model of scientific knowledge, that is, of a knowledge that could be tested and that could lead to accurate quantitative predictions. Most epistemology was essentially the epistemology of physics. A more recent example of the powerful influence exerted by physics on other disciplines is the emergence and rise of molecular biology. Physics played a very important role in the development of neo-classical economics, as was pointed out by Georgescu-Roegen (1971) and by Mirowski (1989). Of course, the physics from which neo-classical economists took inspiration in the construction of their system of knowledge was nineteenth-century physics, and in particular the theory of electromagnetic fields (Mirowski, 1989). Thus, as within physics the view of a deterministic, reversible and in principle calculable universe was gradually giving way to that of a complex, uncertain, irreversible and limitedly knowable universe, the same transition was not occurring in economics, or at least, not in neo-classical economics. The research tradition in economics that recently started to take into account these changes in world-view is evolutionary economics (see Nelson and Winter, 1982; Dosi and Nelson, 1994; Nelson, 1995; Saviotti, 1996). Before entering into any details of complexity or evolutionary theories, let us point out that while the scope for knowledge may now seem more limited, there is a substantial advantage for economics and for the social sciences. Nineteenth-century physics studied a world in which the only possible changes were represented by motion – by displacements of particles with respect to one another. No change in composition, as could be represented by the emergence of new types of entities qualitatively different from those that preceded them, could

easily be taken into account. The changes we observe in economic systems are quite often discontinuities, radical technological innovations, new types of organizations, new activities. That is, qualitative change is an essential feature of economic development, especially in the long term. Theories of complexity and evolutionary theories provide a more appropriate framework for the understanding of such long-term development. We do not expect that the new world-view will give rise to a general theory, capable of explaining all observable events in any discipline. In a sense this general theory would be in contradiction with the newly emerging awareness of the limits of our knowledge. However, sharing a basic framework constituted by some general concepts, metaphors and tools can both give inspiration to ask new questions, and provide coordination between different disciplines. Other disciplines, such as biology and chemistry, have become important sources of methodological inspiration in the social sciences. It must be stated here that the transfer of concepts, models and tools between different disciplines can only lead to interesting and novel questions, but not provide answers from discipline A (for example biological answers) to problems arising in discipline B (for example economic problems). The only common element amongst the theoretical developments that will be described below is the attempt to go beyond the Laplacian dream, which in economics is represented by the equilibrium approach, and to develop the theoretical treatment of a world that is complex, changeable and continuously affected by true novelty. In other words, the presence of qualitative change and the growing complexity of the reality that we observe and study are common components of the different theoretical developments that will be described in the following section.

2. THE LOCAL CHARACTER OF KNOWLEDGE

There are two reasons for which in this chapter and in this book in general we should be concerned with the nature of knowledge. First, if we intend to compare two theoretical approaches, such as neo-classical and evolutionary economics, we are essentially attempting to compare two systems of knowledge. Unless these two systems can be assumed to differ only in their content and not in their methodology, considerations about knowledge are required for their comparison. Second, as was previously pointed out, one of the main differences between neo-classical and evolutionary economics consists in the explicit consideration by the latter of qualitative change, the emergence of new entities during the process of economic development. All these new entities come about as a result of processes of creation and utilization of knowledge. In this sense the production of

knowledge becomes a fundamental concern for economists and for students of economic development.

In what follows, two properties of knowledge that are considered to be very general and applicable to any type of knowledge, from scientific to more empirical and craft based, are described. These two properties do not constitute a complete description of knowledge, but, as it will be seen, they provide a surprisingly powerful basis to analyse processes of knowledge creation and utilization. The two properties are:

- P1: Knowledge is a correlational structure.
- P2: Knowledge is a retrieval or interpretative structure.

2.1 Knowledge as a Correlational Structure

In this chapter it is assumed that a reality independent of human observers exists, in the sense that there are a number of entities constituting the external environment of human beings which cannot be modified at will. The external environment constitutes both a set of resources and a set of constraints for the activity of human beings. Such constraints mean that the ability of human beings to modify it in order to survive is in principle considerable, but limited. No magic wand exists that allows particular outcomes to be obtained at will.

Human beings interact with this external environment by means of their sense organs and by means of a series of enhanced sense organs and tools. Initially, human beings had to rely only on their sense organs for any observations on the external environment. In the course of human evolution they developed enhanced sense organs (for example telescopes, measuring devices, scanners) that allowed them to access parts of the external environment not directly accessible through their primary sense organs. Furthermore, they developed a series of tools (for example axes, hammers) that allowed them to modify purposely their external environment, tools that Georgescu-Roegen (1971) called exosomatic organs. We find here already the basic distinction between two distinguishable but intimately interconnected activities. On the one hand there is a need to observe and to know, on the other hand there is a need to modify the external environment. The activities corresponding to the two needs are clearly separable, at least conceptually, but closely related because it is easier to modify the external environment if we know its structure and properties. In fact, these two needs and the related activities correspond to what we currently call science and technology. Science is the activity that understands and knows our external environment, and technology is the activity that modifies the same environment. Examples of the relatedness of these two activities can be

found from very ancient times, for example in the field of navigation. However, until the second half of the nineteenth century such relationships were more occasional than systematic. The situation is very different today in the societies characterized by a high intensity of R&D.

The distinction between science and technology corresponds roughly to that between ‘to know what’ and to ‘know how’ (Loasby, 1999). To know how allows us to modify our external environment (*ExtEnv*). To know how can be made easier by knowing what happens in the particular subset of *ExtEnv* that we intend to modify. However, the knowledge of the ‘what’ of the particular subset is not always available, thus knowledge of the ‘how’ has to be developed without it. This does not imply that ‘know-how’ is not knowledge, but that it is a knowledge of a different type than ‘to know what’. These differences are by no means easy to understand and to explain and we will come back to them later.

For the time being let us proceed to explain what is meant by ‘correlational structure’. We can identify in our external environment a number of observables, that is of entities that can be responsible for observed phenomena. To each observable we can associate one or more variables that represent and measure different aspects of the observable. In this chapter no particular assumption is made about the truthfulness of the observables and of the variables representing them. In other words, we are not assuming the observables to be real entities that can be observed in an unbiased way by human observers. Observables and variables are mental representations (Loasby, 1999) that allow us to explore the external environment and to establish in it a series of constituting entities and structures. All theories are conceived in the space of mental representations. Of course, we have to assume that our mental representations and the theories that are based on them are isomorphic with *ExtEnv*. This assumption cannot be adequately tested, and its validity can only be judged based on the fact that *ExtEnv* constitutes a set of constraints that cannot be easily overcome, either in order to know or to modify it. Admittedly, this is far from a complete proof, but it can suffice for the purposes of the present chapter; that is, not to provide a complete epistemological foundation for our knowledge, but to outline some properties of knowledge that are valid irrespective of the ultimate validity of the previous hypotheses. What needs to be remembered is that observables and variables are mental representations and that they are parts of a theoretical construction that has to be largely isomorphic with external reality.

If we start, then, from the possibility of detecting observables and of creating variables representing them, we can immediately see that at least some theories are correlational structures. Let us briefly say that knowledge can be subdivided into disciplines or fields, each discipline or field attempting

to explore and explain a subset of the *ExtEnv*. Within this subset the discipline or field identifies observables and variables and establishes the extent of correlation between different variables. Let us consider two examples in order to explain this point better.

$$\textit{The law of ideal gases: } PV=nRT \quad (1)$$

If P is the pressure of a gas, V its volume, n the number of moles of the gas and T its temperature, with R a general constant, equation 1 tells us that all these variables are correlated in such a way that, for example, if we raise the temperature, the volume and the pressure of the gas have to increase in order for equation 1 to still be satisfied. In other words, equation 1 represents the correlation of the behaviour of a number of variables of the gas. Equation 1 is part of a theoretical model, that of ideal gases, in which the atoms or molecules of the gas are considered points occupying zero volume and behaving independently of one another. Such a model is part of a wider theory of gases, and contributes to theories such as thermodynamics or kinetics. This is the most extreme example of a theory as a correlational structure. In this case the correlation takes on a very accurate and quantitative character. As we will see later, this is not always the case. In many cases the correlation provided by a theory can be more qualitative and loose, while still being a correlation. Examples of accurate and quantitative correlations are found mainly in the physical sciences, although they can be found also in the biological and social sciences, even if with a lower frequency.

2.2 Knowledge, Uncertainty and Information

The external environment is knowable because its parts are somehow correlated. If all the components of the *ExtEnv* were totally independent, our knowledge of it would become a list of these component parts. The presence of a correlation between some of the components provides us with an important advantage. If we know a particular subset of *ExtEnv*, that is, according to the previous analysis we know the correlations between and amongst a set of variables representing the subset, we can achieve important savings in information costs. We do not need to measure all the values of the variables correlated, but we can calculate the values of some variables by measuring those of other variables. Here we can already see an economic dimension for knowledge: reduce the information costs required to know and to modify a subset $S(ExtEnv)$ of *ExtEnv*. It must be stressed that information and knowledge are two distinct and very different concepts. Once we define the basic variables of a subset of the *ExtEnv* we can

measure their values. The set of the possible numerical values of these variables is an example of information. Such information does not contain meaning in itself. The concept of information used here is the same used by Shannon and Wiener, that is, it does not carry any meaning, it is purely factual. Any observer not knowing the nature of the subset $S(ExtEnv)$ considered will not be able to make any sense or any use of these numerical values. Previous knowledge of $S(ExtEnv)$ is required, by means of basic variables and at least some correlations. This point will be more fully elaborated in section 2.3, and for the moment it suffices to establish that information and knowledge are two very different, although related, concepts and that previous knowledge of a $S(ExtEnv)$ can reduce the information costs required to gain further knowledge or to modify $S(ExtEnv)$.

Not only can knowledge reduce the amount of information required to understand or to modify a given $S(ExtEnv)$, but it can affect the uncertainty surrounding the given subset. For example, if we want to construct a dam to exploit the energy and water resources of a river we need to know the best position for it, the types and quantities of materials to be used and so on; knowledge of hydrodynamics, of materials science and so on can help us to decide where and how to build the dam. Usually this means that previous knowledge greatly reduces the range of search and thus the corresponding costs. However, the range of search is rarely reduced to zero, in the sense that our previous knowledge gives us the exact position of the dam, the exact quantities of the materials required and the ways in which they can be combined. More likely, our previous knowledge will reduce the uncertainty surrounding the location of the dam, the types and quantities of materials to be used and so on. This reduction in uncertainty can be expected to be greater the more accurate our knowledge is as a correlational structure. It would be wrong, however, to consider that the only effect of new knowledge on uncertainty would be to reduce it. While advancing and improving knowledge of a given $S(ExtEnv)$ is likely to reduce the uncertainty within this subset, it usually leads to the creation of many new subsets (disciplines, specialities) that, especially when they are new, are likely to be affected by very high uncertainty. Thus, whether on the whole the progress of knowledge reduces or increases uncertainty depends on whether the rate of creation of new disciplines, specialities and so on is smaller or greater than the rate at which pre-existing ones are explored. This point will be discussed again in section 2.4.

2.3 Knowledge as a Retrieval or Interpretative Structure

According to information theory, information does not have meaning, it is purely factual. In the previous section it was pointed out that we could

generate information starting from a given theory by measuring a number of properties of the components of the subset $S(ExtEnv)$ studied. The result could be presented as a list of names of entities and of properties accompanied by a list of corresponding numerical values and units of measurement. Examples of such lists would be the frequencies of the electronic transitions of a series of atoms, the frequencies of occurrence of different biological populations in a given habitat, the prices and sales of a series of items in a supermarket and so on. To someone not familiar with the particular branch of knowledge within which these data sets have been generated, the lists would be completely meaningless. A non-knowledgeable reader of these information sets would only recognize in them some numerical value, but he or she would not be able to associate them with any particular entity or subset of $ExtEnv$. Thus, while information does not in itself convey meaning, the same information has to be created in a theoretical context that defines meaning. No information can be created and used without a previous definition of the theoretical context 'containing' it. Thus, while information is not in itself a carrier of meaning, its use by a community of scientists or practitioners involves the shared meanings of the entities or observables, variables and properties measured. Thus information is not generally interpretable by a non-knowledgeable agent or actor, but any information set requires the knowledge of one or more subsets of $ExtEnv$. In this sense knowledge can be considered a retrieval or interpretative structure.

The idea of information as totally devoid of meaning is more plausible in cases where the required underlying knowledge is widely available and taken for granted by all members of a community. For example, a train timetable with a list of times of arrival at and departure from particular places is generally interpretable by most of the members of a reasonably well-educated society. However, the smaller the community knowing a particular subset $S(ExtEnv)$, the more people will be unable to interpret an information set generated within that community.

One of the properties commonly attributed to knowledge is its cumulative character. More advanced areas of knowledge within a given discipline cannot be accessed unless one first learns the most basic areas. Thus any book or paper within a given discipline can only be read by those agents or actors that have a previous knowledge of the same discipline. The more advanced the new piece of knowledge to be learned, the more advanced the knowledge previously required. The previous knowledge held by an individual or organization determines the capacity of the same individual or organization to learn any further and more advanced piece of knowledge within the same discipline. Thus knowledge is a retrieval or interpretative structure both for information sets corresponding to a given discipline and

for other more advanced pieces of knowledge within the same discipline. It can be noticed here that the concept of knowledge as a retrieval or interpretative structure bears a considerable resemblance to that of absorptive capacity (Cohen and Levinthal, 1989, 1990) although the latter was formulated with reference to R&D. R&D is used not only to create new knowledge, but it can increase the capacity of the agents that perform it to absorb similar knowledge. This point will be picked up again in the next section.

2.4 The Local Character of Knowledge

The ability of disciplines and theories to establish correlations between variables or observables is limited. First, correlations can usually be established between a limited number of variables. Analytical equations can contain a very limited number of variables. It is possible to write equations containing a large number of variables, but it becomes increasingly difficult to solve them. Furthermore, even if it were possible to solve equations with a very large number of variables, it would become increasingly difficult to interpret the results. Thus the number of variables involved in each correlation is limited.

The number of observables in the *ExtEnv* is very large, and many if not most of these observables are likely to be interacting. The fact that our ability to establish correlations is limited leads to some peculiar problems. Thus each discipline will explore a given subset of the *ExtEnv*. At best the discipline i will be able to establish correlations amongst all the variables of its subset $S_i(ExtEnv)$. However, even the number of variables of $S_i(ExtEnv)$ is in general sufficiently large that to find correlations amongst all its variables becomes impossible. The best that can be achieved is in general a set of partial correlations, each involving a small number of variables of the discipline. The situation can be better appreciated by representing knowledge in the form of a collection of networks whose nodes are constituted by the variables, and in which linkages indicate the existence of the correlations established in the discipline. We can expect that for any discipline the *connectivity* of the corresponding networks will always remain below its maximum possible value. In other words, we expect to find clusters of connected variables in the midst of a possibly large number of unconnected or poorly connected variables (Figure 1.1).

This implies that not every variable can be reached starting from any other variable. We expect disciplines to differ in their degree of connectivity, and the degree of connectivity of a discipline to improve in the course of time. This discussion already indicates that our knowledge is 'local', that is, that correlation can be established over a limited number of variables constituting a small subset of the observations space of the discipline. Such

Figure 1.1 Example of the network structure of knowledge, showing a limited connectivity. Each of the stars corresponds to a different variable. The linkages correspond to the presence of correlations

observation space is equal by definition to the subset $S_i(ExtEnv)$ of discipline i .

$$OS_i \equiv S_i(ExtEnv) \quad (2)$$

A second sense in which our knowledge can be said to be local is due to the limited range over which any correlation is generally valid. To explain this point we refer back to equation 1, the law of ideal gases. The relationship of pressure, volume, temperature and the number of moles of an ideal gas is only valid within a particular range of values of the variables. As has been mentioned earlier, the atoms and/or molecules of the gas are assumed to behave independently. However, inter-atomic (-molecular) interactions can only be assumed to be zero or negligible at very low pressures and at very high temperatures. As the pressure grows and the temperature falls, equation 1 becomes gradually inadequate to predict the behaviour of real gases. Thus equation 1 can be considered a good approximation for the behaviour of real gases only within particular ranges of values of pressure, temperature and volume. In other ranges of values of the same variables, more complicated models are required in order to represent the behaviour of real gases. This property is not specific to the model considered. All models are

approximations. In order to study a subset $S_i(ExtEnv)$ or a partition of it they assume that a limited number of the variables corresponding to the subset and a limited number of their interactions are more important than other variables and interactions. The model is then always a simplified analogue of reality, containing a lower number of variables and of interactions. The model is then going to be a good representation of reality to the extent that the neglected variables and interactions contribute weakly to the behaviour of the system. Such weak contribution is in general unlikely to persist over the complete range of possible values of all the variables and interactions. Thus we can expect that the validity of most models will be limited to some ranges of the values of the variables and interactions of the subset $S_i(ExtEnv)$. Moreover, even within the range of validity, the ability to correlate variables changes, and it falls gradually as we move away from the ideal conditions of the model.

There is a further way in which knowledge can be considered local. According to the second property of knowledge mentioned above, that of being a retrieval or interpretative structure, any further or more advanced piece of knowledge within a given discipline can only be learned by human actors that already know the fundamental areas of the same discipline. If we now consider that the whole external environment can be subdivided into different subsets, each studied by a discipline, we can realize that different disciplines may have very different or very closely related observation spaces. For example, physics and chemistry have very similar and partly overlapping observation spaces, while physics and anthropology have very different observation spaces. As a consequence, we can imagine ordering disciplines in terms of the similarity of their observation spaces, in such way that neighbouring disciplines are very similar and very far apart disciplines are very different. This point will be developed in greater detail later. Here let us note that the learning ability conferred upon people or agents or actors already holding given pieces of knowledge is not only limited within a discipline. Knowledge of a given discipline A increases the probability of learning a similar discipline B more than that of learning a very different discipline C. If we consider that disciplines are themselves heterogeneous and that they tend to become increasingly heterogeneous in the course of time, we can give the previous considerations a more general form as follows. Assume that the *ExtEnv* can be represented by a very large number of observables and of related variables, and that such observables and variables can be ordered along a monodimensional space. The total observation space corresponding to *ExtEnv* ($O(ExtEnv)$) can be partitioned into subsets that may cover part or all of $O(ExtEnv)$. In $O(ExtEnv)$ we can imagine being able to measure the distances between any two pieces of knowledge, located either within the same discipline or in two different

disciplines. The local character of knowledge can then be represented in the following way.

The probability that a human actor or agent holding at time t a given type of knowledge (actor internal knowledge) can learn another piece of knowledge (external) increases in a way inversely proportional to the distance between the internal and the external knowledge.

This statement can be expressed concisely by means of the following formula:

$$P_{Ki \rightarrow (Ki + Ke)} \propto 1/D_0(K_i, K_e) \quad (3)$$

where $P_{Ki \rightarrow (Ki + Ke)}$ is the probability that a given actor having internal knowledge K_i at time t can learn external knowledge Ke , and $D_0(K_i, K_e)$ is the distance of the internal and external pieces of knowledge in $O(ExtEnv)$.

Let us observe here that the local character of knowledge has some explicit and implicit precedents, although they are less general than the version of the concept presented here. First, Atkinson and Stiglitz (1969) pointed out that, contrary to a common assumption of the production function, innovations do not necessarily affect all the technologies, but only the one that they are designed to modify. Other technologies in the production function remain largely unaffected. At a particular moment in time only a limited number of options exist. In these conditions technological development can no longer be appropriately modelled as a shift in the production function, since it affects only one or a small subset of technologies. Localized technological development leads to a number of important implications. For example, history matters. Atkinson and Stiglitz pointed out that if, as a result of the sharp fall in population due to the plague, European economies had resorted to more capital-intensive techniques, they would not necessarily have abandoned those techniques when the population pressures had subsided. Another important consequence of localized technological development is that the current use of technologies cannot be deduced only from existing scarcity conditions, but also requires an analysis of technological development. Important work in this area has been done by Paul David (1975) who pointed out that localized technological change stems from incremental improvements in a given technology and is not expected to change substantially in a factor-biased direction.

Nelson and Winter (1982) talk about the local character of search in a more restricted sense. In their model each firm at a given time can be represented in input factor coefficient space by a point, corresponding to the technique used by the firm (pp. 180–83). According to their model, the probability that as a result of an innovative process a firm ends up with a different ratio of input factor coefficients is inversely proportional to the

difference between the initial and the final ratios, or equivalently, to their distance in input factor space. This of course implies that local search involves incremental modifications of existing techniques and that ratios near the initial one are the most probable.

A concept perhaps more closely related to the local character of knowledge as expressed in this chapter is that of absorptive capacity (Cohen and Levinthal, 1989, 1990). R&D is not only useful to create new knowledge, but it can also help a firm to learn (absorb) some external knowledge created by another firm or research institution, or simply stored in the scientific and technical literature. The probability that a firm having performed a given type of R&D can absorb some external knowledge depends on the similarity of the internal R&D and of the external knowledge. Both these concepts can be represented as special cases of the local character of knowledge as described in this essay.

Summarizing, we can say that knowledge has a local character because:

1. It can provide correlations only over a small number of variables at a time.
2. It can provide correlations only over a limited range of values of the variables considered.
3. The probability that a human actor holding a given internal knowledge K_i learns some piece of external knowledge K_e is inversely proportional to the distance between K_i and K_e in the observable space $O(ExtEnv)$.

2.5 A Simplified Representation of Knowledge

We can imagine representing the whole observable space corresponding to $ExtEnv$ in an ordered monodimensional space. The ordering criterion would not necessarily be easy to define. We could, for example, order observables according to their level of aggregation, beginning with the smallest and most fundamental and proceeding towards those at a higher level of aggregation within the system. For example, we could start with elementary particles, then proceed to atoms and molecules and then to more complex organisms. Needless to say, such an ordering criterion would not necessarily be easy to apply. However, we do not need to concentrate on this problem now, since a large part of what follows is to a certain extent independent of the precise definition of an ordering criterion. It must also be observed that a mono-dimensional representation is an approximation that will need to be relaxed at some time. Nevertheless, for the time being we concentrate on exploring the considerable analytical possibilities that such a representation can supply.

In this context the whole observation space $O(ExtEnv)$ can be partitioned

into many observation spaces $O_i(ExtEnv)$, each one of them being a subset of $O(ExtEnv)$. A discipline A can be defined as the combination of the actual observation space $O_A(ExtEnv)$ and of all the concepts and tools developed to analyse $O_A(ExtEnv)$. Of course, a discipline is too large and complex to be carried out by individuals with one type of competence. Further division of labour will occur within the discipline. Specialities can be considered as subsets of disciplines, sharing with their discipline some basic concepts and tools and having an observation space which is a subset of the observation space of the discipline:

$$O_{Ai}(ExtEnv) \subset O_A(ExtEnv) \subset O(ExtEnv) \quad (4)$$

where $O_{Ai}(ExtEnv)$ is the observation space of speciality i of discipline A . We can think of further subdivisions, such as theories and models. A theory will then be the subset of a discipline and/or of a speciality that correlates a relatively small number of variables within the set of those corresponding to the observation space of either a speciality or a discipline. This classification could be further developed, but what has previously been introduced suffices for the purposes of this chapter. The principal conclusions of this discussion are that the production of knowledge is characterized by a form of division of labour, in which different subsets of the $ExtEnv$ are assigned to different disciplines, the subset of each discipline being further subdivided into specialities, theories, models and so on. An important question, to which only a partial answer will be given in the course of this chapter, arises now: how are the partitions of $O(ExtEnv)$, corresponding to the different disciplines, specialities, theories, models and so on, arrived at? And, is there only one possible way of operating these partitions? No complete answer will be attempted here, although part of the answer will come from the following discussion.

The monodimensional representation of knowledge can be illustrated graphically as in Figure 1.2. The representation shows that each discipline has a separate observation space, the range of the mono-dimensional space it occupies, and that within its range the explanatory power of the discipline (the curve superimposed upon the range and describing the distribution of probabilities of obtaining a correlation between the relevant variables) varies, reaching a maximum for certain phenomena and declining for other phenomena. The explanatory power curve can be interpreted as the distribution of the probability of providing accurate correlation between variables placed at a given distance along our mono-dimensional knowledge space.

We expect that the newest parts of the discipline, those constituting its frontier, will have a lower probability of correlation than the parts discov-

Figure 1.2 Mono-dimensional representation of the subdivision of the observation space $O(\text{ExtEnv})$ into disciplines. Two disciplines, D_a and D_b are illustrated here

ered and studied earlier that constitute the core of the discipline. Also, we expect that the distribution of probability of correlation of a discipline will not be constant, but that it will vary in the course of time. The dynamics of knowledge generation is obviously a complex problem and we can only begin to scratch its surface here.

If different disciplines and specialities arise as result of division of labour in knowledge generation, we can expect the outcome of this process to be socially useful only if the relevant forms of coordination are present. In our case, coordination would take the form of correlation between the variables of different disciplines. Such coordination would be required in any kind of problem-solving activity based on the knowledge created by different disciplines. It is quite evident that interdiscipline coordination is by no means straightforward and that this coordination difficulty can considerably limit the practical usefulness of discipline-based knowledge. The discussion of this problem cannot be carried any further here. A more extended analysis of the problem can be found in Saviotti (2001).

It is of particular importance for the introduction to this book that the complete observable space encompassing all disciplines is not finite and is not of constant size. This is due to the fact that some observables can be considered given, and that is especially the case in the natural and physical sciences, but other observables are man-made. This is clearly the case in both the social sciences and in the technology-based disciplines. The number of both of these can increase in the course of time. Even observables that have an existence independent of human activities, and that were there all the time, could be discovered at different times. On the other hand, new observables are created as a result of the process of economic and technological development. This is the result of qualitative change, that gives rise to new technical objects, to new types of activities and consequently to new types of organizations and institutions (Saviotti, 1996). Thus, at any

given time we can expect that there will be a set of disciplines that have reached a level of maturity, and that other disciplines will be emerging. Mature disciplines can be expected to have developed a set of standardized concepts and tools on which at least a large part of the profession agrees. On the other hand, emerging disciplines are likely to be still in the process of defining and of classifying observables. We can then expect the connectivity of the network corresponding to the discipline to be very low at the beginning and to increase gradually during the course of the maturation of the discipline. We can then imagine a number of phases through which different disciplines can go: discovery and classification of observables, definition of the concepts and variables required to map and measure the observables, construction of models to correlate the variables of the discipline. Of course we do not expect these phases to occur in a linear way, similarly to what was hypothesized by linear models of innovation. On the contrary, the discovery process of new observables will not be complete when attempts to formulate relevant concepts and variables begin. The formulation of concepts and variables can lead to the discovery of new observables, that will require other concepts and variables. In turn, during these phases the construction of models is likely to lead to a refinement of the variables and concepts developed. In other words, this process is more similar to the one described by Kline and Rosenberg (1986) for innovation, that involves important feedbacks between different components of the innovation process, than to a linear sequence of stages. Clearly, the dynamics of knowledge generation based on these processes is unlikely to be simple. However, without proceeding any further, the results of the previous analysis lead us to the following conclusions:

- Due to interdiscipline coordination difficulties, it is either impossible or very difficult to derive knowledge related to a subset of $O_f(ExtEnv)$ that does not coincide with the observation space $O_{D_i}(ExtEnv)$ of a discipline D_i . This could happen, for example, if $O_f(ExtEnv)$ were to contain more than one discipline, say D_a and D_b . In this case the correlation of the variables of D_a and f of D_b is likely to be more difficult than the internal correlations of the variables of each discipline.
- During the emergence phase of a new discipline it is unlikely that variables and concepts will be so clearly defined as to allow accurate measurements and *ex ante* modelling of new phenomena. Of course, this might differ amongst disciplines depending on the extent to which they can be broken up into simple subsystems. However, the emergence of accurate measurements and models is likely to be preceded by a phase of exploration of the territory constituted by the

phenomena giving rise to the new discipline. As already pointed out, this does not imply that complete clarification of concepts and variables is required before any measurements and modelling can take place. These processes are likely to take place in parallel and with many feedback loops rather than sequentially and independently.

The outcome of this section is that when a new set of phenomena, such as those related to innovation, emerges it is unlikely that accurate instruments of measurement and of modelling are available from the very beginning. This would only be the case if the concepts and methods of a previously existing discipline were applicable to the phenomena in such a way that the explanation of the new phenomena could be deduced from the pre-existing discipline. We can then expect the study of the new phenomena to give rise to a new discipline or speciality, and that during the early phases qualitative exploratory research will dominate up to the time when accurate measurement instruments and modelling techniques will have been developed. In this analysis there is no necessary implication that measurements and modelling will become the exclusive instruments of the new discipline after a given phase. All models are limited, as seen in section 2.4 on the local character of knowledge. Given that the systems studied by economics and by the social sciences are quite complex and not always reducible to simple subsystems, at any phase modelling and measurement have always to be complemented by historical and qualitative studies, even though the former two are likely to become progressively more important.

The previous considerations allow us to discuss different approaches that have so far been used in evolutionary economics. First, following from the previous definition of knowledge, a theory is a structure correlating a limited number of the variables constituting the observation space of a discipline. Second, the correlation of the variables can be more or less accurate and quantitative. Thus, when economic historians tell us that the institutions of a country, and in particular the relative freedom that they allow to their citizens to behave differently, can lead to that country becoming relatively more creative than others (for example Landes, 1999) they are correlating the nature of the country's institutions and its economic performance. Of course, such correlations can rarely be quantitative because the required information is often missing. Nevertheless, they still are correlations of value, both as theories and in terms of their policy implications. For example, if the previous conclusion is accepted, the task for policy-makers becomes one of designing institutions sufficiently open and flexible to foster innovation. The type of theorizing that can be used in most historical or qualitative studies has been defined as 'appreciative theorizing' (Nelson and Winter, 1982). The advantage of appreciative theorizing with

respect to more formal types of theorizing is that the former can be applied to the very many cases where the latter is not applicable, although the results of the former when applied are more uncertain than those of the latter when this is applicable. Furthermore, appreciative theorizing is likely to be relatively more important in the early phases of a discipline or of a speciality, when the basic concepts are still in the process of being defined.

The subsequent development of a discipline or speciality is likely to require measurements and models. Of course, there are disciplines or specialities within which modelling becomes extremely difficult, if not impossible. The following considerations are of greater importance for disciplines such as economics where measurements and modelling are useful, although they cannot be used under all circumstances. Thus the following questions emerge: are the tools used to measure the variables of a discipline specific to that discipline or are there general tools that can be used for many types of measurements in many disciplines? Before proceeding to give an answer, however tentative, to this question, we have to observe that it would be very advantageous if such general tools existed. The greater the number of measurements or of modelling situations to which these general tools are applicable, the lower the amount of information and knowledge that must be stored within each discipline. Irrespective of the desirability of such general tools, we can expect that each discipline will tend to generate at least some tools that are specific to it. If the observables of a discipline are generated without any *ex ante* connections to those of other disciplines, it is quite likely that the variables designed to represent them will be different from those corresponding to the observables of other disciplines. This is not to deny that in some cases it is possible to reduce the variables of a discipline to those of another. Indeed there have been some very successful examples of this reduction during the history of science. For example, both chemistry first and then biology have made immense progress by reducing some of their variables to those of physics. In some cases reductions of this type have been attempted or applied to cases where the results are more mixed. A typical example of this situation can be found in the influence that physics exerted on the development of neo-classical economics, especially in its early stages (Mirowski, 1989; Georgescu-Roegen, 1971). In general we can expect that, if the observables of a discipline are defined independently of those of other disciplines, and if the subsequent development of the discipline tends to enhance this specificity, not all the variables of D_a will be reducible to those of other disciplines. Given that measures are usually based on some previous if ill-defined theoretical concepts, we can expect a number of the tools of a discipline to be specific to it. Again, this does not deny the possibility and often the advantage of borrowing variables and concepts from another discipline. In a dynamic sense we can expect new

observables to give rise to new variables and to new tools, thus enhancing the diversification of the overall tool set of human knowledge, while some variables and tools of different disciplines will gradually be correlated and reduced to one another. For what concerns the task of this chapter, since evolutionary economics has been developed mainly in response to the need to analyse technological innovation, we can then expect some concepts and tools specific to this task to have been created. If all the concepts and tools of a speciality were specific to it, such a speciality would become a separate subset of human knowledge, not connected to the general network of knowledge. Neither of these extreme cases is likely to apply to evolutionary economics. The real situation is likely to include both the construction of specific concepts and tools and the reduction of a part of these to more generally used ones. The chapters of this book provide us with interesting examples of new empirical tools and of approaches to modelling that have a considerable degree of specificity to evolutionary economics.

We can then follow the development of evolutionary economics as beginning with an initial phase, where the need to study innovation was satisfied by means of largely empirical studies with very limited support from neo-classical economics, and being followed by phases where first conceptual generalizations and then more precise measurements and modelling took place. The initial empirical studies, carried out in the 1960s and 1970s, constituted a sort of natural history of innovation (Coombs et al., 1987). The generalizations that followed beginning from the 1980s were, for example, those leading to the concepts of dominant design (Abernathy and Utterback, 1975), natural trajectories and technological regimes (Nelson and Winter, 1977), technological guideposts (Sahal, 1981) and technological paradigms (Dosi, 1982). Early modelling exercises (see for example Silverberg et al., 1988) have been followed by an increasing range of new models, each one using broadly similar assumptions but largely different and specific tools. This is leading to the requirement for a greater coherence amongst evolutionary models (Valente, 1999), coherence that in terms of the framework of this chapter can be reduction of the variables and tools of each model to a common set of variables and tools. The term 'reduction' is used here because the variables and tools of each model should be reduced to some common and more fundamental variables and tools.

In the following chapters a number of concepts which emerged recently will be the object of measurements and of modelling exercises. For example, Chapters 2 and 3 will both deal with particular types of networks: of innovation in biotechnology in Chapter 2, and of collaboration between engine and aircraft frame producers in Chapter 3. The concept of networks has been acquiring a growing importance in economics recently. Early analyses of networks were mostly due to sociologists (see for example

Callon, 1989, 1992; Powell, 1990). Economists started to become interested in networks as a consequence of the increasing frequency with which they occur in a number of key industries and technologies (Hagedoorn and Shackenraad, 1990, 1992; Teubal et al., 1991; Teubal and Zuscovitch, 1994; Langlois and Robertson, 1995; Freeman, 1991; De Bresson and Amesse, 1991). This is a clear example of how tools of analysis are gradually developed. Some of the studies cited were based on appreciative theorizing, others used quantitative tools that were often specific to each study. Without expecting all of them to converge rapidly in a common set of variables and tools, we can expect a trend towards an increasingly differentiated toolbox, in which at least some tools will become standardized. Thus the general tension between differentiation and standardization that we can expect in many disciplines, specialities and so on seems to be operating in the development of the analysis of networks. In this context, Chapters 2 and 3 constitute examples of a mature and increasingly rigorous use of network techniques and concepts. In Chapter 2 Pammolli and Riccaboni study the networks of innovation in the pharmaceutical industry during the period 1978–97. They claim that biological technologies can derive from two regimes, the first based on research techniques and hypotheses that stay coupled with specific biological hypotheses and are specific to given fields of application (co-specialized technologies), and the second characterized by new generic research tools and techniques (general-purpose technologies). Correspondingly, the firms taking part in the networks studied can be originators or developers. Each of the two types can be co-specialized or transversal. They study the structural evolution of the networks by means of digraphs, by identifying the actors with the vertexes of the graph and the relationships with the edges. The authors claim that the topological methods of graph theory are superior to any approach focused on variables defined at the level of individual nodes, because the latter cannot convey information on the global structure of the system. There is a high degree of appropriateness of the tools used to the subject matter of the chapter. Pammolli and Riccaboni make a particularly rigorous use of digraphs, that enable them not only to provide an accurate description of the networks of innovation existing at different times, but also to detect a structural transition during which the roles of the actors present in the networks change. In their chapter digraphs are combined with econometric analysis. The authors are careful to stress the complementarity between the two types of analysis by pointing out that econometric work on its own can rarely offer guidance in the identification of the most meaningful parametric models in fields which are new and characterized by processes of radical technological change. Thus the inductive structural analysis based on digraphs provides the necessary basis on which econometric work can be built.

Another example of the use of networks is provided in Chapter 3 by Bonaccorsi and Giuri. They study the evolution of industrial organization in the commercial jet engine industry. They claim that there are increasing returns both in the aircraft industry and in the aircraft engine industry, but that the evolution of their industrial structure is very different. The sharply increasing concentration in the aircraft industry contrasts with the decreasing concentration and the increasing instability of the aircraft engine industry. As a consequence the number of firms present in the industry has increased during the course of its evolution. The explanation of this different behaviour is provided by the changing network structure in the aircraft engine industry. In the analysis, measures of industrial structure and stability, such as the Herfindhal and Parsigian indexes, are combined with network measures, such as density and centrality of actors, to provide a representation of the relevant aspects of industry evolution. The chapter is interesting both from a methodological point of view, for its use of network techniques, and in reference to the industry life cycle (ILC) model (Klepper, 1996; Klepper and Simons, 1997). In spite of increasing returns to R&D the evolution of the aircraft engine industry does not follow an ILC model. What seems to cause the deviation from the model in the present case is the structure of the network of vertical relations that limits the effect of increasing returns at the firm level.

In both of the previous two chapters networks play a very central role in the analysis. Economists have only recently discovered networks, presumably due to the very strong individualist orientation of most of neo-classical economics. Although as a metaphor they may be common to different research traditions, networks are a particularly appropriate concept in evolutionary economics. Networks can be considered the structure of social reality. The links existing within any network are generally not all the possible ones, since they map existing interactions amongst social actors. Of course, patterns of interaction while being potentially durable are not eternal. They may change, and sometimes their changes are discontinuous, amounting not to a slight variation of an existing structure but to a structural change. In a sense, the network metaphor is even too general: any pattern of interaction can be described as a network. In the previous part of this chapter even knowledge was represented as a network of observables or variables. Yet this generality can offer the advantage of common techniques that are in principle applicable to very different cases. Although this advantage is in principle available, it is not clear that at the present stage it is used. For example, a representation of the networks of knowledge in particular cases can be obtained by means of lexicographic analysis, a component of scientometrics. By means of this technique it is possible to obtain charts representing graphically the knowledge base of a firm. The same technique is

not directly applicable to the analysis of the networks constituted by firms, research institutions and so on. It is then more likely that the growing interest in networks will for the foreseeable future be developed by means of different and not necessarily easily compatible tools, each adapted to a specific application. This is not surprising given the partly exploratory and inductive character of many evolutionary studies. In spite of the construction of a common conceptual background and of some shared tools, the process of standardization has not proceeded as far as in other disciplines or specialities. To the extent that the observables and phenomena that are discovered by means of evolutionary studies are radically new and qualitatively different with respect to those studied by other research traditions, we cannot expect them to emerge with ready-made and highly standardized tools. On the contrary, it seems more likely that the construction of empirical and analytical tools will be preceded by appreciative theorizing and will be a gradual process. Different tools specific to particular applications can be expected to increase their mutual compatibility once the basic exploration of new regions of knowledge space is sufficiently advanced. We can thus expect network techniques and models to play a growing role in the future development of evolutionary economics.

Chapter 4, by Geuna, compares the chemical and pharmaceutical sectors in the USA and in the four largest European countries, as concerns their sources of knowledge and their patterns of scientific specialization. The approach here is based on the construction of indicators of the properties of the science system of the different countries that the author intends to measure. The development of new indicators has by now a considerable tradition both in studies of innovation and in evolutionary economics. The very name 'indicators' tells us that they are not proper measures. Indicators provide quantitative estimates of phenomena that are not sufficiently well known to be measured. The construction of indicators is not the consequence of a previously developed accurate knowledge of a given phenomenon, but a part of the exploration of the same phenomena that will eventually lead to a more accurate knowledge. Thus the construction of indicators is very closely related to appreciative theorizing. We can imagine that a more accurate knowledge will be arrived at by means of a sequential process beginning with a very approximate definition of entities, variables and properties, continuing with the definition of relevant indicators, which will subsequently allow the testing of preliminary hypotheses, and will lead to an improvement of the basic conception of the problem. In turn, new and improved indicators will allow the testing of more advanced hypotheses, leading to a further change in the basic conception. Geuna's chapter provides examples of indicators of properties that had not before been investigated, such as 'knowledge integration' and

'knowledge persistence'. The former would be high when the index of specialization for a particular subfield of science (for example medicinal chemistry) is comparably high in all categories (for example applied research, basic research). The latter is high when the indexes of specialization of different fields and their degree of knowledge integration are stable in the course of time. Both these properties can be conceived as part of studies based on appreciative theorizing. Furthermore, both are properties that have very close policy implications. Thus the formulation of problems and their subsequent evolution are strongly influenced by the policy requirements of knowing how a particular system (for example the UK pharmaceutical research system) works with respect to others, and what can be done to improve its performance.

In Chapter 5 de Almeida studies the evolution of the technology of electric motors (EMT). The analysis makes reference to product and technology life cycle models and measures the changes that have occurred in the variety of the technology during its evolution. The variety of the EMT technology is measured by means of either the informational entropy function or the Weitzman function. Both functions were developed to be used in a biological context, that is to measure diversity, defined as the number of species that can survive in a given habitat. The adaptation of this concept to the analysis of technologies has been developed by Frenken et al. (1999). The possibility of measuring variety by means of the two functions can be understood intuitively as follows. First, if the number of distinguishable species, either biological or technological, increases, the quantity of information required to describe them and measured by the informational entropy function, increases. Thus, the informational entropy function increases as the variety increases. Second, the Weitzman function measures the diversity of a system that can be described as a genealogical tree, whose diversity increases with an increase in the number of branches and in the distance between branches.

The variety of the EMT technology measured by these two functions falls in the early period of its evolution and increases in the later phase. This result is interesting if compared to the product and technology life cycle models that often foresee a convergence towards a dominant design during the process of maturation of the technology. Leaving aside the content of this debate, which will be dealt with more appropriately in Chapter 5, it is important here to notice that the treatment of variety as developed in this chapter bears a greater similarity to that of diversity as used by biologists than to that of variety used by economists. The reason for this difference is the interest in long-term developments present in evolutionary economics rather than in the short-term implications of variety that were traditionally stressed in economic theory. Thus, here as well as in the case of networks,

the adoption of new measurement techniques is preceded by a conceptual analysis that defines the objectives of the new techniques.

In Chapter 6 Larrue studies the performance of a particular research consortium, the USABC, that was responsible for the development of batteries for electric motors to be used in cars in the USA. The author considers research consortia as organizational devices that during the emergence phase of a technology become identifiable as credible representatives of an emerging industry. The chapter thus stresses, although implicitly, that technologies cannot develop without being institutionalized. This chapter is clearly a case study. Only one consortium is studied, thus no generalization can be attempted on a statistical basis. However, some interesting general problems are discussed. For example, the chapter is focused on the emergence phase of a new technology. The author claims, rightly, that this phase gives rise to organizational questions different from those of more mature phases. If a technology is created in an a-institutional form and only subsequently acquires its own institutions, this has to occur during the emergence phase. Thus the objective of research consortia can be defined as the institutionalization of an emerging technology. The chapter is based exclusively on appreciative theorizing, but it relies on a number of generalizations previously developed in evolutionary economics. To begin with, the concentration on the emergence phase involves the conceptualization of technological evolution as a discontinuous process, in which the different phases of the technology life cycle have distinctive features. Concepts such as dominant designs (Abernathy and Utterback, 1975), technological regimes (Nelson and Winter, 1977, 1982) and paradigms (Dosi, 1982) are specific expressions of the discontinuous nature of technological evolution. Thus appreciative theorizing has here reached the stage where it is based on a common set of concepts. This chapter is an example of the continued usefulness of case studies. New phenomena are likely to be studied in small numbers at the beginning and not to have a statistical representation. In a sense the availability of statistics is itself a form of institutionalization of the new phenomenon. If the process of institutionalization is what one wants to study, a different approach has to be used. In the very early phase of the life cycle of a new technology, case studies remain an indispensable component of the toolbox that can be used. Of course, case studies can be very different depending on whether they can make use of a previously developed conceptual background or whether they are entirely empirical.

In Chapter 7 Bel and Bourgeois study the persistence of innovative behaviour amongst firms in the petroleum refining industry. The persistence of innovative activity, a problem first studied by Geroski et al. (1997), is of considerable importance. The results of this chapter indicate that in this industry, innovative activity tends to be sporadic for most firms. The

same result is obtained in Chapter 8 by Le Bas, Cabagnols and Gay, although with a sample of French firms distributed over all the sectors. Thus, the distribution of innovative activity amongst firms is not only very asymmetrical in a cross-section sense, but also as concerns its time dynamics. Bel and Bourgeois find that persistent innovators in the petroleum refining industry tend to be those firms that have a large portfolio of innovations, a result which is again confirmed by Le Bas et al. for the sample of French firms. To the extent that this result can be corroborated by similar ones in other industries, it constitutes interesting evidence of the cumulative character of knowledge. Of course, the authors are aware that such a generalization would be too hasty, given the possibility that industry-specific features influence the persistence of innovative activity. These two chapters provide examples of the use of a number of techniques, such as the Kaplan–Meier estimators or the Weibull regressions, to study the phenomenon of persistence of innovative activity.

The next section of the book, Chapters 9–12, deals with modelling. The chapters here are less numerous, but deserve to be considered in the context of applied evolutionary economics because most of them combine simulation with empirical work and with appreciative theorizing. These chapters underscore the general reliance of evolutionary models on an at least partly inductive approach, and the widespread use of simulation to solve equations that are often too complex to find analytical solutions. A number of other features shared by evolutionary models will be discussed later in this ‘Introduction’.

Chapter 9 by Pyka, Krüger and Cantner discusses the changes that have recently been observed in the world distribution of income, changes that have been called ‘twin peaks’ because the distribution that has been emerging is bimodal. A bimodal distribution has been explained by other models, but the authors of this chapter use an evolutionary approach based on the dynamics of knowledge distribution in the economic system. In their treatment, all countries start with a similar basic knowledge, but some of them undergo transitions to higher productivity states while others fall behind. The determinants of the transitions to either higher or lower (relative) productivity are the ability to exploit extensive technological opportunities, infrastructures and obsolescence. The first two contribute to transitions towards higher productivity, while the third is responsible for countries falling behind in the productivity league. The transitions of all the countries are represented by the master equation, a tool initially developed in physics but adaptable to the social sciences and capable of predicting discontinuous transitions. Essentially, some countries are more successful than others at exploiting extensive technological opportunities and construct technological infrastructures that give them a competitive advantage,

making catch-up by laggard countries increasingly difficult. Discontinuities in knowledge production at certain times, and the cumulative character of knowledge in other periods, are the central elements in the model of Chapter 9. The authors also determine empirically the changes in world income distribution by measuring the kernel density of a data set constituted by the Penn World Tables. The evolution predicted by the model matches the empirically observed distribution very well.

Chapter 10 by Kwasnicki presents a sectoral model of firm dynamics, and uses it to discuss the relationship between punctualism and gradualism in economic development. The structure of the model has several features similar to or common with one of the Nelson and Winter (1982) models, but differs in its treatment of routines and innovation. Routines, that are here represented as strings, can be ‘active’, that is used by firms, or ‘latent’, stored for further use. The set of routines used by a firm may evolve by means of four basic mechanisms: mutation, recombination, transition and transposition. In most cases these mechanisms give rise to small modifications, unless a phenomenon called ‘recrudescence’ takes place. Recrudescence determines firms’ ability to search for ideas that are so original and far-fetched as to be sometimes apparently insane. Without discussing all the results of the model, but concentrating only on the punctualism–gradualism dichotomy, firms can change and evolve on a fitness landscape, but they cannot move away from a local optimum unless recrudescence takes place, thus dramatically changing the nature of firms’ routines. Then, although most of the time the development predicted by this model may be gradualist, unless punctualism occurs at particular, even if short times, economic development is limited. The chapter contains also a valuable discussion of general modelling problems in economics, and in particular a comparison between social sciences and engineering models. Like several other evolutionary models, Kwasnicki’s relies on the use of biological metaphors, but their use in this chapter is not in any sense a passive replication of the concepts in an evolutionary economics context. The use of biological metaphors is here based on an assumed morphological similarity between biological and technological evolution. Biological metaphors are used to ask new questions or to frame old ones differently, but their answers are derived based on economic analysis and not on a superficial extrapolation of the answers to similar biological problems.

Chapter 11 by Windrum discusses the conditions required in order to develop a model of technological succession. Why do new technological species emerge and others become extinct even in the presence of increasing returns? What limitations are inherent in increasing return models and what modifications of these models would be required in order for technological succession to be possible? What factors other than those internal to

a technology are required in order to explain technological successions? These are some of the main questions raised in Chapter 11. In the end, the author proposes a matrix of performance characteristics combined with the distribution of the users' preferences. Quite apart from the usefulness of the solution proposed, this chapter represents an example of the appreciative theorizing that is required before a good evolutionary model can be constructed.

Chapter 12 by Geroski and Mazzucato is an evolutionary model of selection in the presence of learning. The system studied is composed of two firms, one which uses a traditional technology, the other which invests in a 'learning' technology, whose performance improves in the course of use, since its production cost falls with increasing output. The initial production cost of the learning firm is higher than that of the traditional firm, but it can improve in the course of time as production accumulates. The chapter is evolutionary because it concentrates on two main features: first, the mechanisms that create differences and thus contribute to the heterogeneity of agents; second, competition between firms and technologies does not necessarily lead to the survival of the fittest, due to the possibility of increasing returns and of other positive feedback mechanisms. In particular, the authors try to evaluate the consequences of 'myopic selection' on the one hand and of 'endogenous selection' on the other hand. Myopic selection would operate, for example, if only product market selection existed and if this rewarded only current fitness. On the contrary, capital market selection, by focusing on future expected fitness, can partly compensate the effect of product market selection, thus opening up opportunities for innovation. The presence of capital market selection leads the authors of this chapter to diverge from replicator dynamics which, as they say, would be appropriate to describe only product market selection. The structure of this model is clearly evolutionary for several reasons: first, for the concentration on the heterogeneity of agents; second, for the concentration on competitive selection, focusing on its myopic and endogenous aspects.

As it was previously pointed out, evolutionary economics is a research tradition still at an early phase of its development. The mixture of appreciative theorizing, of case and historical studies, of modelling and of new empirical studies provided in this book cannot be considered an exhaustive sample of present work within this approach. In addition to the small size of the sample considered here, the continuing development of evolutionary economics is likely to produce changes in the types of studies that are likely to prevail in future. To the extent that radically new concepts keep being introduced, we can expect appreciative theorizing to continue to play an important role, and both measures and simulation techniques to follow with a delay and with a considerable extent of fragmentation. On the other

hand, a slowing down of the rate of introduction of novelty could be expected to lead to a greater standardization of tools of both measurements and simulation. The tension between these two extreme situations certainly exists now in evolutionary economics, and we cannot expect it to disappear soon in the development of this research tradition.

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