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L'hypothèse Lamarckienne remise en question

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SOME LAMARCKIAN THEMES IN THE THEORY OF GROWTH AND ECONOMIC SELECTION: A PROVISIONAL ANALYSIS

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Abstract

The purpose of this short note is to explore some properties of a simple evolutionary model in which firms learn and improve their competitiveness in accordance with their growth history. The origins of the argument are traced to the relationship between guided learning and patterns of technical progress. The economics of selection are shown to depend upon the rate of learning such that the variety in unit costs generates competition which feeds back to regenerate that variety. In short, the paper introduces Lamarckian feedback into the replicator dynamics of growth and selection.

Résumé

L'objectif de cette brève note est d'explorer quelques propriétés d'un modèle évolutionniste simple dont les firmes apprennent et améliorent leur compétitivité en fonction de l'histoire de leur croissance. L'origine de cet argument est tracée jusqu'aux relations entre l'apprentissage et les cheminements du progrès technique. On voit que l'économie de la sélection dépend du taux de l'apprentissage de telle manière que la variété des coûts unitaires engendre une concurrence qui agit par rétroaction sur la variété. Ainsi, l'article introduit une rétroaction lamarckienne à l'intérieur de la dynamique de réplique de la croissance et de la sélection.

The purpose of this short note is to explore some properties of a simple evolutionary model of technological competition and structural economic change. A concern with structural change requires little justification since the ever changing pattern of economic relations between firms, sectors, regions

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and nations is the most insistent of all the characteristics of modern capitalism, the ultimate stylised fact, if I may put it in that way. The value of the evolutionary approach is precisely its ability to come to terms with the restless nature of the economic system. As is any evolutionary model the principal elements are variety in behaviour within a population of competing economic agents, and well defined selection mechanisms which eliminate behaviours which fall below a certain standard and change the relative proportions within the population of the remaining "superior" behaviours. From this flow the three tasks of evolutionary economic theory: to comprehend the economic mechanisms which generate variety in behaviour; to articulate clear selection mechanisms and their properties; and, to identify mechanisms such as increasing returns and endogenous innovation, which provide feedback from the process of selection to the generation of variety. With respect to the first and third of these tasks the Lamarckian heritage is of major importance. The Lamarckian tradition in biology is a controversial one on the grounds that behaviours acquired as a result of experience cannot be transmitted to future generations (Mayr, 1982). But in the social and economic sphere this particular objection is redundant (Hodgson, 1993): a variety of institutional and cultural memory devices permit the codification and transmission of acquired experience through time and make it possible to deploy legitimately a Lamarckian theory of adaptive development. Experience gained at one point in time may thus lead to developments in behaviour which improve the selection advantages of an individual or organisation at future dates. Far from being in conflict with the principles of selective evolution, the Lamarckian tradition enriches the plausible sources of variety upon which evolutionary change depends. In the following we will therefore sketch some Lamarckian elements contributing to economic change, elements which link changes in the competitive behaviour of firms to the operation of the selection process. More precisely we will review recent literature on technical change which emphasises learning-like behaviours, and we will develop a simple model of economic evolution with Lamarckian feedbacks [1].

I. LEARNING AND LAMARCK

Within the modern synthesis of evolutionary theory, it is usual to summarise the forces of evolution in terms of "chance and necessity" (Mondod, 1963) or "blind variation and selective retention" (Campbell, 1987). In each case the forces which make for variety are acting independently of the selection process, there is neither learning nor the formation of expectations to shape

behaviour. In the economic and social sphere this is unsatisfactory for obvious reasons. The behaviour of individuals and organisations are shaped by their past experiences and by the connections between a memory of the past and an anticipation of the future. From this simple observation flow the possibilities for path dependent and irreversible behaviours and the phenomenon of inertia, of which "lock-in" is an extreme form much discussed in recent literature (Dosi and Metcalfe, 1991; Arthur, 1989; David, 1993). The Lamarckian theme that past selection events can generate future behaviours which improve the chances of subsequent selection, has an immediate claim to attention which it does not have in the natural world.

To make progress with this theme requires that attention be paid to two general characteristics of decision making processes. The first is their boundedly rational, inductive nature, in which rules and their meta-rules are formulated and operated subject to requirements of satisfactory performance. In many cases it is possible and instructive to equate the meta-rules with strategies. The second characteristic is the role of learning phenomena, and hence memory in the generation and revision of behavioural rules. The learning based organisation is the natural corollary of the boundedly rational organisation. This is particularly so with respect to those behaviours which generate innovation and underpin variety in behaviour. Indeed students of technical change have pioneered a range of learning concepts in relation to innovation, learning by doing (Arrow, 1962), learning by using (Rosenberg, 1978), learning by scaling (Sahal, 1985), which suggest a foundation for Lamarckian principles of endogenous technical progress. To these perhaps we ought to add the not insignificant category of learning by forgetting. In a recent paper, Malerba (1992) has emphasised that learning phenomena have a number of attributes in relation to technological change: learning is costly and occurs in different parts of the firm; it involves the interaction between internal and external sources of knowledge; it is cumulative; and, it supports localised and primarily incremental innovation. He distinguishes six categories of learning activity which we may re-group together into three broad categories: learning which is a joint poduct of activities producing and using artifacts; learning which involves the interaction with external sources of knowledge located in other institutions, whether other firms or science and technology agencies; and, internal, directed learning which is typically organised around a formal R & D programme. Malerba convincingly argues that the different kinds of learning activity are productive of different kinds of technological change so that firms with different learning structures will generate di patterns of innovation.

II. GUIDED LEARNING AND PATTERNS OF TECHNICAL PROGRESS

One of the most easily recognisable features of technical change is its none random nature, and this we argue, arises from the necessarily guided nature of learning process. Several recent developments in our understanding of technical change have greatly clarified this chreode like property of technical change.

The first is the important distinction made by Layton between different dimensions of technology, as artefact, as skills and as knowledge. Each dimension has its own particular accumulation mechanism and supporting matrix of interacting institutions. While artefacts are the basis around which firms act out the competitive process, it is knowledge and skills which define the competence of a firm and it is the competence dimension which is the focus of learning activity. It makes a considerable difference whether the results of learning are economic to codify or whether they remain in the tacit realm, for this affects mechanisms of transfer of technology within and between organisations and the degree to which advances are appropriable by rivals. Tushman and Andersen, for example, have employed the distinction between competence destroying and competence enhancing changes in technology as a way of capturing the radical nature of technological change and its implications for the competitive process. The second aspect of the recent literature on technical change is the insistence upon the paradigm like properties of technologies. Dosi was the first to articulate this point clearly, and the issue is not whether the idea of scientific paradigm can be carried over more or less exactly to the study of technology but rather that paradigms provide shared cognitive frameworks for the individuals and institutions seeking to advance the technology. In this they provide a framework to identify opportunities and a set of constraints on the kinds of technical improvement which can be considered. In short they are a device for dealing with the tyranny of combinatorial explosion. If we think of a technology as a set of design concepts integrated together to form a design configuration the force of this point can be made immediately. With "n" possible design concepts there are $2^{n-1}-1$ possible integrated technologies, an impossibly large number for n as small as one-hundred. What paradigms do, is abstract from this set of all possible concept combinations the much smaller subset which have been discovered and demonstrated to be workable. Once a workable design configuration has been established it provides a framework within which technologists can define problems and identify solutions: it becomes the framework for incremental artefact improvement within a stable

broad knowledge and skill base. From this it is a short step to characterising paths of advance as trajectories (Dosi, 1982) or as innovation avenues (Sahal, 1985) or as dominant designs (Abernathy and Utterback, 1978; Utterback and Suarez, 1993). Each label simply captures the idea of canalized or chreodic development, that is, change within constrained opportunities. An excellent account of these issues has been provided in a study of the engineering of the Britannia railway bridge (Rosenberg and Vincenti, 1978). They summarise the emergence of the chosen design configuration for the bridge in these terms: "In a broader and more general sense, the engineers learned something perhaps more important. By struggling with their problem and forming conceptual models, they learned to think synthetically about the design of an important class of wrought iron structures. This *intellectual framework* (emphasis added) enabled them to combine empirical data, theoretical understanding, and artful surmise—each limited and incomplete—to attain their practical goal. A splendid example of the examplar properties of a technological paradigm and its role in guiding the development of technology. We would simply add here the further insight that, in setting up learning mechanisms to exploit specific technological opportunities, organisations inevitably develop a degree of commitment to the required mode of learning is this commitment to a specific learning structure and associated competencies which helps explain their inability to adapt to the emergence of new design configurations based on different knowledge paradigms. Hence they have great difficulty in adapting to the change in the set of technological possibilities and in many cases are forced out of the industry (Cooper and Schendal, 1976; Abernathy and Clark, 1985, Starbuck, 1983; Zuscovitch, 1986).

The third and final aspect relevant to the Lamarckian argument is the systemic properties of a technology. This occurs most obviously at the artefact level but equally it applies to the underlying design principles and their interaction. Thus, Henderson and Clark (1990) have usefully distinguished between technical change in the components of a system and technical change in terms of the system architecture, the way these components interact. This leads them to a fourfold innovation taxonomy which fruitfully expands the usual distinction between and incremental and radical change. For present purposes however, the significance of a system perspective is its implications for the guided nature of technical change. Compatibility between components and balance in their performance capabilities provides a binding constraint of the development of the system as a whole. To make the most of improvements in one component or sub-system, it is necessary to improve complementary elements and in some cases engage in a thorough re-design of the systems architecture. Several authors have drawn attention to this phenomenon as a guide to learning effects, thus Rosenberg (1980) writes of imbalances and focusing devices, Sahal (1985) of technological guideposts, and Hughes (1983) of reverse salients. Each of these concepts is based on a systemic view of technology and the opportunities and pressures which shape innovative activity. We shall note here that the systems perspective provides a hierarchy of levels at which change can occur, as system divides into sub-systems and components in repeated fashion, such that radical change at one level can equally be interpreted as incremental change at higher levels. On the same grounds as systems shape opportunities to learn, they also place interrelatedness constraints on what might be achieved (Frankel, 1955). An improvement in one sub-system can only be adopted if the costs of engineering compatibility with the rest of the system keep the overall portfolio of changes economically feasible. The final aspect of the modern literature which builds on the Lamarckian theme is the importance of user-supplier interactions in the development of technology (Lundvall, 1993). The central issue here is that technologies are not represented by single innovations but rather by sequences of innovations which emerge as signposts along the path of development of a particular design configuration (Georghiou *et al.*, 1986). The nature of each innovation sequence reflects the co-evolution of technology and market application, guided by experience and shaped by the cognitive expectations of suppliers and users.

Taken together, these four aspects of modern research into innovation processes provide a suggestive background to a Lamarckian perspective on economic evolution. Making these themes more precise will be a major challenge but signs are already emerging of new approaches and methods of analysis. One intriguing possibility will be the application of genetic algorithms to model the systemic and paradigm-like nature of technologies (Goldberg, 1989; Kauffman, 1993). Thinking of technological systems as collections of genetic strings which have to be organised to match a specified technology template and which mutate and cross over subject to specified rules (including random rules) is an immediately appealing prospect. Moreover, the related notions of fitness and the properties of the selection environment are aspects of this approach which permit a natural methodological bridge with the wider economics of evolutionary change. However, all this lies in the realm of future prospects. Our task now is to turn to the second of the evolutionary themes, the nature of economic selection, and to consider how it operates in the presence of intentionally simple feedback mechanisms, which mimic some Lamarckian aspects of the endogenous interaction between competition and the distribution of behaviours which drives competition.

III. EVOLUTIONARY COMPETITION AND ECONOMIC CHANGE

The principal theme of economic evolution is the explanation of how heterogeneous or asymmetric behaviour gives rise to patterns of structural change. In achieving this a number of issues have to be addressed. First and foremost the premise of representative behaviour ceases to be the foundation of the analysis: such essentialist thinking is quite foreign to the evolutionary perspective. Rather, a population perspective is adopted in which the entire distribution of behaviours shapes the pattern of change. Secondly, the evolutionary argument must explain how variety in behaviour connects with patterns of change. In particular it has to generate non-arbitrary measures of economic variety which follow from the particular economic problem to which evolutionary principles are being applied. In this context we claim that a theory of competition has three tasks: to define appropriate measures of variety; to establish how they are constructed; and, to relate them to the patterns of change which define the rate and direction of evolution. For example, in the following analysis, the relative importance of the competing firms, as measured by their market shares, is continually changing. Some firms are increasing share, others are losing share, yet others may be stationary, and these patterns are dependent on the particular differences between firms in competitive characteristics and on the market environment in which these differences are evaluated. Some competitive characteristics will be technology dependent, some will reflect the behavioural rules or routines (Nelson and Winter, 1982) which define each individual firm. Now in the presence of complex patterns of change it is natural to seek summary measures which draw togther the many individual movements into a set of statistical measures. The evolutionary theory of competition provides these measures in terms of the moments of the appropriately defined distributions of competitive characteristics. One of the clearest statements of this claim is provided in the work of the eminent English geneticist, R. A. Fisher. Working in terms of basic evolutionary principles, principles which are independent of their application to a genetic problem, Fisher established his "fundamental theorem of natural selection" that the rate of change in average behaviour in a population of competing organisms is proportional to the variance in behaviour in that population. Since the variance is a statistic of unambiguous sign this gave evolution a direction and a velocity. Now we need not concern ourselves with the controversy surrounding this proposition [2] for it is indeed a special case. Nonetheless it is of considerable interest as an example of what I will term "Fisher's principle", namely that the rate of change of one moment of the population behaviour distribution is functionally dependent on the current state of other moments. Thus the special case of the fundamental theorem is one in which the rate of change of the first moment is proportional to the current state of the second moment.

The principle is one of considerable power and generality as the following argument will seek to demonstrate, and it presents a number of challenges to a theoretical account of evolution. What distinguishes the evolutionary approach is its focus on diversity of behaviour as the primary source of change in economic structure, that is, the relative importance of rival behaviours.

Before we turn to these issues we need to clarify the nature of the dynamic processes considered by the evolutionary method. The traditional method of dynamic analysis in economics has a well defined structure which involves the identification of an equilibrium state of rest (stationary or moving, as in Harrod's growth theory) which is then subjected to perturbations or shocks in the presence of which the tendency to restore the equilibrium can be investigated. Powerful as this method is, it suffers from a number of drawbacks. Not only are there difficulties associated with the presence of multiple equilibria, it has to be assumed that the convergence process is path independent, in that the fact of being out of equilibrium does not alter the equilibrium point around which the dynamics is conducted. For "small" perturbations this is no doubt permissable but this leaves entirely open the question of large perturbations and far from equilibrium behaviour. More fundamentally, a theory of equilibrium behaviour *simpliciter* cannot of its nature establish the properties of out of equilibrium behaviour which essentially reduces to the invocation of *ad hoc* adjustment processes. The disequilibrium dynamics is, as it were, tacked on as an afterthoughts as in the famous examples of tatonnement and stability in market price formation.

Our evolutionary argument proceeds down a different path based on the dynamics of replicator systems [3] which define the disequilibrium dynamic processes. The driving forces behind the dynamics of the system are not defined with reference to any state of rest (attractor) but rather in terms of the current distribution of behaviour (competitive characteristics) around the current population average. The dynamics may seek out an attractor but that is not entailed by the argument. In this sense, replicator dynamics is a discovery process and admirably suited to the study of open ended evolutionary systems. We shall apply replicator principles to the long period dynamics of capacity accumulation in an industry without making any reference to the notion of a long period position. The dynamics of evolution are permitted to discover such a position under certain assumptions but if it exists it is only one of

the elements determining the movement of the system at a moment in time. Knowledge of any long period position is not presumed nor is the argument incapacitated if a long period position should be changing rapidly because of exogenous events.

Two final points are in order. The first concerns the application of that much abused word equilibrium in an evolutionary context. Suffice it to say that it is important to distinguish equilibrium as a coherent interaction between various economic agents, how their actions fit together, and equilibrium as a state of rest. Equilibrium as a coherent interaction, a structure of relationships, is central to our story, equilibrium as a state of rest is not. Secondly, none of the ensuing argument depends on any hypothesis for or against maximizing behaviour at the level of the individual agent. What matters is stability of behaviour and differential behaviour across individuals. More important is the question of whether, irrespective of the foundations of individual behaviour, the system as a whole can be said to lead to outcomes which reflect a maximum principle. For simple replicator processes, this is certainly the case, the more general question remains open.

IV. LAMARCK, PENROSE EFFECTS AND THE ECONOMICS OF SELECTION

To illustrate the central principles of an evolutionary model, I will take a very simple Lamarckian model of competition in which the competitive advantages of firms depend on their current and historical performance within their selective environment. The general way we capture this is through the invocation of Penrose effects, namely that constraints on a firm's competitive performance, do not depend on its scale but rather upon its rate of expansion (Penrose, 1959). We shall explore this in two ways. The first is through the managerial constraint, that the firm's managerial capacity at any point in time is limited and the more management resource which is devoted to expanding the firm the less is available for controlling unit costs. Hence, there are decreasing returns to expansion, growth imposes a cost penalty. The second constraint is a learning constraint, a firm's management acquires new knowledge as a result of the experiences gained through growth. A static firm learns nothing new, only a growing firm benefits from the insights gained from changing its size. In short, learning depends on confrontation with the new experiences generated by growth. Both of these mechanisms provide Lamarckian dimensions to the evolutionary process. On the one hand, the greater the growth rate of the firm the higher are its unit costs, so more competitive firms have their competitive advantages diminished by their success. This provides us with a negative feedback mechanism in relation to current performance in the environment. On the other hand, through the learning effects, firms are able to enhance their competitive advantages as accumulated growth experience is translated into lower unit costs. This provides a positive feedback mechanism. In short, these feedback mechanisms link the behaviour of the competing firms to their performance in the selection environment, which is precisely the Lamarckian point.

Let us now formulate this general idea more precisely. Consider a population of firms producing the same product using a constant returns to scale (in the static sense) production process indexed by unit cost level $h_i(t)$. The market shares of the firms, $s_i(t)$ define the structure of the population of competitors at a point in time. The output of each firm at that point in time is limited by its current capacity, which it expands at rate g_i, providing its profits are positive. In order to keep unessential complications in the background, we let the market be perfect, a uniform price is faced by all firms, and we let total market demand grow at a constant, exogenous rate, g.

The core of our argument now depends on the relation specified between the growth performance of the firm and its unit costs.

Specifically, define the unit cost function for the i-th firm as

$$h_i(t) = kg_i(t) + b_i + \varphi[E_i(T, t)] \tag{1}$$

when b_i is a firm specific constant, k is a constant the same across all firms, and $E_i(T, t)$ is the measure of the accumulated experience of the firm since its founding date T. The function $\varphi[\bullet]$ translates accumulated experience into the current unit cost level with $\partial\varphi/\partial E_i < 0$. To be even more specific, we define $E_i(T, t)$ as follows:

$$E_i(T, t) = E_i(T, T)\exp\left\{\int_T^t g_i(t)\,dt\right\} \tag{2}$$

a relation between the accumulated growth history of the firm and its index of experience. It follows that the rate of change of each firm's unit costs is given by:

$$\frac{dh_i}{dt} = k\frac{dg_i}{dt} - \propto h_i g_i \tag{3}$$

when $\propto$ is the common experience elasticity [4] linking changes in the index E_i to changes in the firm's unit costs. We now have a rich pattern of dynamic forces operating on the underlying distribution of cost behaviours, for the rate of change of any firm's unit costs depends upon the change in its growth

rate and the non-linear interaction between its current growth rate and its current unit cost level. This permits us to close a very important loop in the evolutionary process. As we shall now show, the pattern of selection depends on the prevailing distribution of unit costs which is itself continually shaped by the changes in the relative positions of the firms which are a consequence of selection. Thus far we have described a simple population of firms, differing only in their unit costs, in part as a result of "Lamarckian" influences arising from their history of growth within the selection environment. We must now connect this variety in their cost behaiour to the process of market selection. The first step is provided by the accumulation mechanism, each firm expanding its capacity according to the rule (Nelson and Winter, 1982; Metcalfe, 1992):

$$\begin{aligned} g_i(t) &= f(p(t) - h_i(t)) \qquad \text{if } p(t) - h_i(t) > 0 \\ &= 0 \quad \text{otherwise} \end{aligned} \tag{4}$$

where f is defined as the given propensity to accumulate. Given our concern with the role of cost differences we set this propensity at the same value for all the competing firms. The second step follows from the dynamics of the market shares, namely:

$$\frac{ds_i(t)}{dt} = s_i(t)[g_i(t) - g] \tag{5}$$

where g is the overall growth rate of the market. On combining (4) and (5) we immediately uncover the fundamental replicator dynamics of competition between the rival firms, thus:

$$\frac{ds_i(t)}{dt} = fs_i(t)[\bar{h}(t) - h_i(t)] \tag{6}$$

For any firm which is profitable, the rate of change of its market share depends on the distance between its unit costs and the average unit costs defined across the population of growing firms, $\bar{h}(t) = \sum s_i(t)h_i(t)$. Notice that the dynamics of the system do not depend in any sense on a comparison of unit costs with some notion of what they might be in some state of hypothetical equilibrium, when competition has ceased to operate and the market shares are therefore stationary. The set of equations (6), one for each firm, provide a complete description of the dynamics of structural change in the industry, firms growing or declining in relative importance according to whether they are more efficient or less efficient than the prevailing population average. At the lower tail of the distributions we can assume that firms exit the industry when their unit costs fall below the prevailing price, although this part of the selection mechanisms is not important in the current context.

It is standard procedure in evolutionary analysis to summarize this complex pattern of development in terms of changes in the moments of the distribution of behaviours across the population. Thus, in terms of Fisher's principles the rate of change of the population mean, for fixed values of $h_i(t)$, is given by:

$$\frac{d\bar{h}}{dt} = \sum \frac{ds_i(t)}{dt} h_i(t) = -f\, V_s[h(t)] \tag{7}$$

when $V_s[h(t)]$ is the prevailing variance in unit costs within the population. By similar reasoning, the variance evolves according to

$$\frac{dV_s[h(t)]}{dt} = -f\, K_s[h(t)] \tag{8}$$

being the third moment of the population distribution. Here we see the deeper structure of evolutionary dynamics, population moments of one kind change according to the state of higher order moments. It is the content of a specific economic theory of competition which indicates how these moments are to be measured, in this case using the market shares as the appropriate weights, and how the moments are to be related together in Fisher principle fashion.

However, in the current context we need to go beyond the formulation contained in (7) and (8) for not only are the unit cost elements not given, they are changing endogenously as a consequence of the selection pocess. It is here that our two Penrose effects come into their own, to give the Lamarckian dimensions to the competitive process.

V. LAMARCKIAN FEEDBACK AND SELECTION DYNAMICS

To explore this issue in greater detail define $u_i(t) = h_i + \varphi[E_i(T, t)]$, as that component of unit cost which is independent of the managerial constraint. Thus $h_i(t) = u_i(t) + kg_i(t)$ and, summing across the dynamic firms, $\bar{h}(t) = \bar{u}(t) + kg$. Hence the cost deviations around average performance can be written as $[h_i(t) - \bar{h}(t)] = [\bar{u}_i(t) - \bar{u}(t)] + k[g_i(t) - g]$. In place of (4) we then have

$$g_i(t) = \frac{f}{1+fk}[p - u_i(t)] \tag{9}$$

and

$$g_i(t) - g = \frac{fk}{1+fk}[\bar{u}(t) - u_i(t)] \tag{10}$$

the two relations which, as in (4) and (6), summarize the dynamics of selection. In short negative feedback is exerting a cost penalty on each

firm, such that $(g_i(t)-g)$ is damped relative to the primary cost difference $[u_i(t) - \bar{u}(t)]$.

By decomposing the unit cost variance into its component elements, we see that

$$V_s[h_i(t)] = V_s[u_i(t)] + k^2 V_s[g_i(t)] + 2k\, C_s[u_i(t),\, g_i(t)],$$

where $C_s(u_i\, g_i)$ is the covariance between g_i and u_i across the population. However, the dynamics of selection, in Fisher principle fashion, imply that $C_s(u_i\, g_i) = \frac{-f}{1+fk} V_s[u_i(t)]$, that $V_s[g_i(t)] = f^2 V_s[h_i(t)]$, which together imply

$$V_s[h_i(t)] = \frac{1}{(1+fk)^2} V_s[u_i(t)] \tag{11}$$

Notice that the variance of $h_i(t)$ is damped relative to the variance of the underlying values of $u_i(t)$. In (11) we see a further typical line of evolutionary argument, the economics of competition translating one primary dimension of a population distribution into a related secondary dimension.

From (10) we see that the fundamental replicator dynamics of the competitive process are unchanged in form since

$$\frac{ds_i(t)}{dt} = \frac{fk}{1+fk} s_i(t)[\bar{u}(t) - u_i(t)] \tag{12}$$

which means that the evolution of the system at any point in time is linked to its past history via the experience effects of each firm as they relate to $u_i(t)$. In this sense, competition is history dependent.

To draw the analysis together it is sufficient to focus on the evolution of average practice unit costs, since this now responds to two pressures: that of pure selection; and that of "innovation" as determined by the endogenous Lamarckian effects. Instead of (7) we have the much richer specification.

$$\frac{d\bar{h}}{dt} = \sum \frac{ds_i}{dt} h_i + \sum s_i \frac{dh_i}{dt} \tag{13}$$

which from (3) we can write as:

$$\frac{d\bar{h}}{dt} = \sum \frac{ds_i(t)}{dt} h_i + k \sum s_i(t) \frac{dg_i(t)}{dt} - \propto \sum s_i(t)\, h_i(t)\, g_i(t) \tag{14}$$

After further simplification (*see* Appendix) this reduces to

$$\frac{d\bar{h}(t)}{dt} = -f[1 + fk - \propto] V_s[h_i(t)] - \propto \bar{h}(t)\, g \tag{15}$$

or in terms of $\bar{u}(t)$

$$\frac{d\bar{u}(t)}{dt} = \frac{-f}{(1+fk)^2}[1 + fk - \propto] V_s[u_i(t)] - \propto [\bar{u}(t) + kg] g \qquad (16)$$

Whichever form we take, the combined outcome of pure selection and the feedback terms is always progressive, the average level of unit costs, whether defined in terms of h_i or u_i, must decline over time. However, their individual effects fall into two parts. There is a second component to each of (14) and (15) which is reminiscent of the Verdoorn laws, the faster the growth rate of the market the faster the rate at which learning economics accumulate, and the faster the proportionate rate at which average practice costs decline for a given market structure. This component depends directly on the experience elasticity, $\propto$. By contrast, the first component in (15) or (16) reflects the quite different operation of Fisher's principles, as they relate to changes in the structure of the population. In turn this involves a direct effect which depends on the coefficient $f(1+fk)$ and an indirect experience related effect dependent on the elasticity $-\propto$. The direct effect is the interaction between selection and the managerial Penrose effect (the dependence on k) while the conflicting, indirect effect relates to the interaction between selection and the within population distribution of growth experience, (the dependence on E_i). Thus the direction of the Fisher effect, linking the variance in cost behaviour to the rate of improvement in cost behaviour, depends on a comparison between $1+fk$ and $\propto$. Unless $1+fk > \propto$, the variance in unit costs works against progress, pace Fisher.

VI. CONCLUSION

There is a great deal more which can be said about even this simple exercise but space does not permit further elaboration and we already anticipate that the principal conclusions are clear. In an evolutionary model of competition, the challenge is to explore the pattern of change within a population in terms of the different behaviours of the rival firms. We have focused upon one such component of rival behaviour, unit costs of production, but the argument generalises readily to other dimensions of competitive performance such as product quality (Metcalfe and Gibbons, 1989). The general dynamics of change at population level are summarised in terms of the so-called Fisher principles and our task has been to show that these fundamental principles remain intact when we allow the rival behaviours to vary endogenously, in Lamarckian spirit, as a consequence of the selection process. This we

have done by reference to the famous Penrose effects, relating a firm's cost behaviour to its growth rate, which is, in turn, dependent on the position of that firm within the population distribution. The Penrose effects fall into two categories. One is static, it reflects a managerial constraint and leads to a tradeoff between a firm's efficiency and its growth rate. The second is dynamic, and reflects the cost-reducing experience a firm gains from expanding its activities, a form of dynamic increasing returns or learning by growing. At this point the connection with our opening remarks on technical change can be completed, for growth in the application of a technology is precisely a route to learning how that technology can be improved. Thus the broad principles of Lamarckian change can indeed be given a precise expression in the evolutionary context of technological competition via positive and negative feedback effects, or as Lamarck would have put it use and disuse. This is all we have attempted to have shown, at most a first step in the further analysis of the co-evolution of technologies and markets.

Appendix [Proof of (14) and (15) in the text]

The expression to be simplified is $\frac{d\bar{h}}{dt} = \sum \frac{ds_i}{dt} h_i + \sum s_i \frac{dh_i}{dt}$, where the summation is taken over all the firms with $g_i > 0$. For simplicity, the time indices to s_i, h_i are dropped. Since

$$\frac{ds_i}{dt} = f s_i [\bar{h} - h_i]$$

it follows immediately that the first term is the pure Fisher effect

$$\sum \frac{ds_i}{dt} h_i = -f V_s[h]$$

where

$$V_s(h) = \sum s_i (h_i - \bar{h})^2$$

To evaluate the second term we have from (3)

$$\frac{dh_i}{dt} = k\frac{dg_i}{dt} - \propto h_i g_i$$

and from (6)

$$\frac{dg_i}{dt} = f\left[\frac{dp}{dt} - \frac{dh_i}{dt}\right]$$

However, since the aggregate growth of the market is constant it follows that $dp/dt = d\bar{h}/dt$.

Therefore

$$\frac{dh_i}{dt} = fk\left[\frac{d\bar{h}}{dt} - \frac{dh_i}{dt}\right] - \propto h_i\, g_i$$

$$= \frac{1}{1+fk}\left[\frac{fk\, d\bar{h}}{dt} - \propto h_i\, g_i\right]$$

Hence

$$\sum s_i\, \frac{dh_i}{dt} = \frac{1}{1+fk}\left[fk\, \frac{d\bar{h}}{dt} - \propto \sum s_i\, h_i\, g_i\right]$$

$$\frac{1}{1+fk}\left[fk\, \frac{d\bar{h}}{dt} - \propto (C_s\,[h,\, g] + \bar{h}g)\right]$$

where $C_s\,(h,\, g) = \sum s_i\,(h_i - \bar{h}_i)\,(g_i - g)$ is the covariance between h_i and g_i. Immediately we see that $C_s\,(h,\, g) = -f\, V_s\,[\bar{h}]$.

Combining the results, yields

$$\frac{d\bar{h}}{dt} = -f\, V_s\,[h] + \frac{1}{1+fk}\left[kf\, \frac{d\bar{h}}{dt} + \propto f\, V_s\,[\bar{h}] - \propto \bar{h}g\right]$$

or $\frac{d\bar{h}}{dt} = -f\,[1 + fk - \propto \beta]\, V_s\,[h] - \propto \bar{h}g$ which is (15) of the text.

The proof of (16) follows immediately by noting that $\bar{h} = \bar{u} + kg$ and $V_s\,[h] = \frac{1}{(1+fk)^2}\, V_s\,[u]$. Remember that all these exercises are being worked out for a given market growth rate.

Notes and references

1. The Lamarckian theme is of course much broader than we are allowing for in this paper on which the reader is referred to the outstanding recent book by Hodgson.
2. As far as I can establish, the first application of Fisher's fundamental law in the economics literature is to be found in Nelson and Winter p. 243.
3. Hofbauer and Sigmund, 1988; Silverberg *et al.*, 1988.
4. Defined as $\propto = (\partial\varphi/\partial E_i)\,(E_i/\varphi) < 0$.

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COHERENCE, DIVERSITY OF ASSETS AND NETWORKS: TOWARDS AN EVOLUTIONARY APPROACH

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Abstract
The concept of network is nowadays taking a growing importance in the academic literature as well as in the strategic behaviour of firms. The purpose of this paper is to investigate why there is a growing interest for networks, what is the theoretical root of the concept and how the phenomena of learning and the coherence and diversity of assets are related to it. To do so we shall make use of the theory of evolutionary economics. Networks appear then as a specific organisational form, for the evolutionary process undergoing in modern manufacturing systems.

Résumé
Le concept de réseau remplit un rôle croissant aussi bien dans les travaux des chercheurs que dans le comportement stratégique des firmes. L'objectif de cet article est de clarifier cette tendance en proposant au concept un fondement analytique et en le situant par rapport aux phénomènes d'apprentissage de cohérence et de la diversité d'actifs. Nous utiliserons pour ce faire la théorie évolutionniste. Le réseau apparaît alors comme une forme organisationnelle spécifique au processus d'évolution du système productif moderne.

The concept of network is nowadays taking a growing place in the academic literature as well as in the strategic behaviors of firms. Considerable efforts have been recently realized to clarify the concept and to set up precise typologies of different network forms (Thorelli, 1984; Powell, 1988; Grandori, 1991). However, many theoretical and practical issues remain at stake: this

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