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Self-organization and economics—what is new?

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Abstract

The theory of self-organization, discussed recently in the sciences, provides an abstract, general description of evolutionary processes. This paper argues that it is also of some relevance to economics. Insights into the functioning of dissipative systems—the basic unit of self-organization—can shed new light on the economic theory of the means of production and long-term growth. Moreover, as the economic counterpart to self-organization, the classical 'invisible hand' conjecture concerning the self-regulation capacity of markets is incomplete. Self-organization theory suggests to extend it to account for the self-amplifying features of innovative change in the markets. © 1997 Elsevier Science B.V.

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1. Introduction

In the bio-sciences—biology, biophysics, biochemistry—'self-organization' has been established as a label for a new, overarching, paradigm focusing on the emergence and change of living structures during evolution. These structures are generated and maintained due to flow processes by which the systems are in exchange with their environment, first of all obtaining inflows of free energy. Typically, a continuous variation in the flows does not produce continuous but abrupt and often striking changes in the particles' organization, i.e. the visible, dissipative, structures which the particles form (see Prigogine, 1976; Haken, 1977; Jantsch, 1979; Kauffman,

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1995). The patterns of non-linear dynamics discovered in the processes and the intellectual tools developed to analyze them are similar across the disciplines. They can be categorized into two kinds of pattern: self-regulating processes (negative feed-back) which stabilize given structures and temporarily self-augmenting processes (positive feed-back) which destabilize given structures and, thus, are instrumental in establishing new structures. In the transition between the two an instability is passed. The dynamic interaction between these two features of self-organization has turned out to be a powerful basis for generalizations.

The question may therefore be raised as to whether something new can also be learned in economics when an attempt is made to apply the concepts of self-organization developed in the bio-sciences to the economic domain. The question has already attracted some attention (see Lesourne, 1989, 1992; Foster, 1994) and, although the term 'self-organization' has no great significance in economics, the very concept indeed seems to be relevant in several respects. On the one hand, all living systems are dissipative structures. Man's modern, largely extended forms of subsistence through agriculture, industry, and transportation are no exception. Thus, in terms of biophysics, the productive basis of the economy may well be considered an extension of nature's self-organization. This has been claimed already by Georgescu-Roegen (1971), but the implications of such a view for economic theory are only slowly being recognized (e.g. Faber and Proops, 1993; Gowdy, 1994).

On the other hand, economic theory has since long been concerned with a problem of self-organization of its own (Witt, 1985). It arises from the question of how a regime of division of labor comes into being (or 'organizes itself') so that productive and consumptive activities of the members of society take place in a more or less coordinated way. As is well known, an answer has been provided with the notion of the 'invisible hand' (Smith, 1979; Hayek, 1967), i.e. with the idea of an interaction process entailing coordination as an unintended side-effect in the pursuit of self-interest. This is a genuinely economic theory of societal self-organization, of order or structure in the behavior of the particles of a social system, which even predates the discovery of the notion of self-organization in the sciences. A discussion of the role of self-organization in economics should, therefore, help to come to grips with two different though, as will turn out, related problems. First, in which way are the obvious biophysical constraints—as any dissipative system has to face them—accounted for in the economic theory of production and growth? Second, with regard to the coordination problem, are there any new insights to be gained by confronting the notions developed in economics with the concept of self-organization as developed in the sciences?

The present paper deals with the two problems as follows. Section 2 explores how human economic production can be interpreted as an extension of nature's self-organization. The interpretation requires to put in perspective two quite different views of the means of production: labor and capital in the traditional economic understanding versus energy, matter, and knowledge in the understanding of natural dissipative systems. As Section 3 shows, the 'stylized facts' of economic growth look quite different in the two perspectives. Correspondingly, it is not the determinants of capital accumulation and consumption that need to be explained in the first place, but the phenomenon of changing regimes of production and the driving forces behind these changes. Section 4 prepares the ground for an explanation by turning to the economic version of self-organization. It explores how, in the economic coordination process—which, of course, is the basis for economic growth—self-regulating and self-augmenting features occur so that the process can indeed be considered an instance of societal self-organization. However, while the self-regulating properties of the price mechanism are traditionally emphasized in economics, the self-augmenting tendencies have been grossly overlooked. Yet it is precisely these self-augmenting features which are crucial when it comes to explaining regime changes and long-term economic development. In order to present this argument in more detail, a simple model illustrating self-augmentation in an economic process is outlined and discussed in Section 5. Section 6 offers some concluding remarks.

2. Nature's self-organization extended

As any living system, human beings depend on a steady energy and material throughput or consumption in order to maintain their 'far-from-(thermodynamic)-equilibrium' state which is what 'life' means in biophysical terms. The basis of Homo sapiens' capacity to move, feed, procreate, and entertain himself is a metabolism in which energy taken up in the form of food is transformed into mental and physical work—the latter as far as the muscles' power reaches. As will be argued in this section, modern man has, thanks to his innovativeness, been able to get rid of the constraints of his own muscles' power through tapping and instrumentalizing non-human energy sources. On that basis an expansion of the natural metabolism into the modern economy's production and consumption patterns has been possible. Nonetheless, the modern economy is still a dissipative system for which the same basic physical laws apply as for any other dissipative system. This means, in particular, that it is always bound to operate on the level up to which the necessary flows of free energy can be made available.

Standard economic theory of production and growth is not very helpful for coming to grips with this fact. Its basic categories, labor and capital as homogeneous factors of production, do not suit well an approach which discerns economic production and growth as an extension of nature's self-organization.[1]

In the perspective of the latter, the fundamental categories would rather be energy, matter, and knowledge. Labor and capital, by contrast, appear as 'extremely hetero-

[1] Even a rudimentary reference to nature once made in the form of an additional factor 'land' has practically been abandoned. For a good discussion of the role of land in the history of the human extension of nature's self-organization see Hesse (1993). The homogeneity problem is treated extensively in Kurz and Salvadori (1995, chap. 14). As Weissmahr (1992) has shown, the choice of the factors labor and capital as basic categories since the classics has been influenced by a strong interest in the conflict over the distribution of the fruits of production, i.e. income, among the members of society. The interest seems to have been nourished further by the historical fact that capital owners and labor differ significantly in their capacity to save resources from current consumption in order to accumulate the means of production necessary for economic growth.

geneous aggregates ··· (that) have all the scientific validity of the medieval elements of earth, air, fire, and water' as Boulding (1981, p. 28) has put it. The case of labor is of particular significance. Inspecting more closely what human labor provides (per unit of time), two clearly distinct things can be identified. On the one hand there is physical work, i.e. force multiplied by displacement—a measure for the transference of energy. On the other hand mental work is being done, i.e. psychic attention and effort are devoted to some task, e.g. working on the solution of some problem—a measure for human knowledge creation/application. Owing to constraints in the amount of time and attention, there is a trade-off relationship between the two kinds of work. In the historical process, the systematically changing relative importance of the two kinds of labor service offers important insights as to how, with respect to the technological side, the extension of nature's self-organization could be achieved.

Up to the neolithic, physical work was the predominant feature. The picture changed somewhat thereafter as man learned to domesticate animals and to make use of the physical work which these animals can provide. However, it was not before the last four centuries that a growing, explicit, technological knowledge made two things feasible at the same time: a large-scale substitution of human physical work through non-human energy sources and a real boost in the production volume. Wind and water power, wood, coal, oil, natural gas, and uranium were tapped one after the other (see Marchetti, 1980). Human physical energy input successively lost its character as a constraint for the growth of economic production. At the same time, the increasing division of labor generated ever larger flows of commercial information which demanded mental work for being transmitted, processed, and registered. Thus, in a historical process that accelerated strongly over the past few centuries, the quality of labor input changed from physical work into mental work so that, today, the employment of human labor for carrying out physical work is of no more than minor importance. Usually, it is confined to transformation of materials where, due to the small scale or a unique character of the tasks, installing respective equipment is not economical, e.g. in repair, the crafts, and the classical services.

A striking example for the process is the development of the effective capacities of different forms of transport (see Usher, 1954, chap. 1, with reference to work by J.E. Holmstrom). Transport service is identical to human physical work input where freight is carried by a human porter, the simplest 'technology' which for thousands of years accounted for a lion's share of transport services. On a route length of one mile, a trained human porter is estimated to move up to 1750 tons of freight per year. A heavy pack animal, by contrast, is rated at up to 3500 tons of freight and saves the carrier most of his own physical work. Mental work (per unit of time) for supervising, guiding, and caring activities is, of course, necessary. The bullock wagon, a heterogeneous composition of materials, energy, and knowledge, combined with animal working power is estimated at moving up to 8640 tons per route mile per year. A horse-drawn wagon may even have an effective capacity of 15 000 tons, basically because of higher speed which demands more advanced know-how in wagon construction. The really dramatic leap in transport capacity occurred, however, when water-, railroad-, and highway-based transport systems were created. For that task to be achieved, several prerequisites had to be fulfilled: large-scale energy supply, several major technological innovations—mental work at large, and a large-scale accumulation of resources for realizing both the necessary facilities and the particular equipments.[2] On such a basis then, a truck with a load capacity of 30 tons can, for instance, carry 3 000 000 tons of freight per route mile per year. The physical work input by the trucker is negligible; the mental work in terms of psychic attention and effort, however, is crucial.

In order to understand how the dissipative system economy could develop into its present appearance, a closer inspection of the factor (technological) knowledge and its generation by mental work is necessary. Any dissipative system can increase its production only by increasing energy and material throughput. The economy is no exception. However, the way in which energy and materials are combined in the economic production process is contingent on the state of technological knowledge applied. Each technology used implies a certain upper bound on feasible energy and materials. These bounds can be shifted through switching to more advanced technological knowledge—provided this is available. The generation of new knowledge is a result of mental work, though not the only one. It is necessary, therefore, to distinguish the services of human labor further into non-creative and creative forms of mental work according to whether existing knowledge is being applied or new knowledge is being created.

Non-creative forms of mental work, like controlling, monitoring, and administrative works, associate a manifold, but usually clearly defined, set of states with actions to be taken. Operating on already existing knowledge, the cognitive skills necessary to perform the tasks are usually comparatively easy to learn. The same holds for many information transmission, registering, and processing activities characterized by a set of routines that have to be performed repetitively on clearly defined sets of information. By contrast, creative forms of mental work, like scientific and technological research, planning, organizing, and conceptualizing of problems, involve tasks in which not yet defined pieces of information have to be associated and the results have to be construed. This means that new knowledge is being generated. Usually, substantial knowledge and experience is necessary for competent associations and interpretations to be carried out.

3. The stylized facts of long-term economic growth reconsidered

The regime switch from production processes relying on human physical work input to production processes based on large-scale flows of non-human energy would

[2] In order for non-human energy to be utilized, some means of transforming it into work are necessary. They were provided in the form of—historically changing—material arrangements as wind and water mills, steam and combustion engines, etc. These materials had themselves to be extracted, transformed, and combined with other materials, with energy, and with knowledge—and all these resources had to be withheld from immediate consumption. Such a mixture of materials, energy, and knowledge in varying compositions—an 'extremely heterogeneous aggregate' (Boulding, 1981) indeed—is what economic theory considers the homogeneous factor capital.

not have been possible without a significant input of creative forms of mental work. Nonetheless, it was non-creative mental work that absorbed labor in the first place, where it has been increasingly set free from doing physical work since the industrial revolution. (The overall decline in employment that went hand in hand with the substitution of human physical work is nowhere more clearly visible than in agriculture, a sector which still produces pretty much the same array of goods as it did before the energy revolution.) The reason was that once the limitation of muscular power as the basis of physical work had been technologically overcome, mechanical devices in the form of 'machinery', e.g. like the weaving machine or the tractor, could be designed. Fueled with non-human energy, they were able to multiply and accelerate mechanical routines formerly carried out by the worker's hand. As long as the resources for realizing the conceived technological solutions could be made available, and as long as the markets absorbed the ever growing volume of goods and services thus produced, ever more machinery could be built up. Machinery, however, needs to be operated—controlled, monitored, tooled up, and administered—the tasks of non-creative mental work as defined above.

On the other hand, the fact that the production process became more and more dependent on explicit technological knowledge implies a growing importance of creative mental work inputs and a correspondingly growing share of it in employment. Different from the practical insights and skills which had usually been transmitted and improved on the job through imitation and personal communication, the transition to a systematic, large-scale generation, storing, and transmission of knowledge requires specialization in mental work. Scientific and technological knowledge needs to be newly acquired by each new generation of the work force. This accounts for a significant share of the mental work input necessary for solving creative tasks in modern economies, even if it is not (directly) paid for in the labor markets and, therefore, not accounted for in employment statistics.

In the further expansion of the dissipative system economy a stage appears to have been reached now where, once again, a systematic substitution of one form of labor by another one is under way. The industrial revolution focused on material arrangements for transforming flows of non-human energy into work and for multiplying and accelerating mechanical processes. Recent technological efforts aim at the automation of controlling and monitoring functions and of the transmitting, registering, and processing of information. This has become possible through the invention of electronic devices (once again on the basis of non-human energy flows being available). Where, in the case of the industrial revolution, the effect was a large-scale substitution of human physical work, it is now the substitution of non-creative mental work that had once been introduced in place of physical work. Again the replacement permits a multiplication and acceleration of work formerly done by humans, in this case information processing, by orders of magnitude. Labor is once more set free because of a strongly reduced number of employment opportunities in controlling and monitoring those automata that have taken over and in processing the remaining information as it has been filtered out by automatic information processing. What remains, thus, is employment of labor in the creative forms of mental work. This kind of employment is indeed likely to grow, not only as a consequence of the significantly larger knowledge necessary for developing automation devices and programming their tasks. The maintenance and transmission of a growing body of scientific and technological knowledge also demands increasing human resources.

It is worth noting that the interpretation just given is much in line with what is known as Fourastié's law. This stylized description of the transition process in many countries, from agriculture to industry and further to the service sector as the leading sectors in terms of employment, has never been made sense of in a convincing way in terms of the standard theory of economic growth.[3] No wonder, then, that the present interpretation is quite different from economic growth theory which is a story of capital accumulation (as has lately been reconfirmed once again by 'new' growth theory, see Romer, 1986; Grossman and Helpman, 1991; Crafts, 1995). Long-term economic development is viewed here as a sequence of regime switches in which knowledge about the potential and the economic feasibility of non-human energy sources interacts with a characteristic change in the quality of human work input in the production process. An important side-effect of splitting up labor into various different qualities is, of course, to make the role of the hidden 'natural' means of production—energy, matter, and knowledge—visible, as it suggests itself once the economy is interpreted as a dissipative system. Indeed, on this basis, the historical record of economic growth can be summarized in a way that differs remarkably from the 'stylized facts' that were once formulated by Kaldor (1957), who emphasized increases in the productivity of labor, capital intensity, real wage and roughly constant values of capital productivity, real interest rate, wage and rent shares.

The most obvious facts can be put as follows (see Fritsch, 1991). The tapping of non-human *energy* sources and the substitution of human physical work by the non-creative forms of mental work resulted in a strongly growing energy flow utilized in production per hour worked, i.e. in an increasing energy intensity. At the same time, the availability of free energy beyond the limitations of the human physical power allowed a mechanization of the transformation of materials at large so that the output produced per hour worked, i.e. the productivity of labor, increased as well. Since, however, the former ratio grew faster than the latter, the energy input per unit of output, the energy coefficient, increased.[4] Coinciding with that development the price of energy per unit, e.g. measured in mega-joules, fell strongly relative to

[3] See Fourastié (1952 chap. 2). The lead of the agricultural sector correlates with the predominance of human physical work input for maintaining subsistence. The lead of the industrial sector correlates with the rise of non-human energy utilization and mechanization and the transition from human physical work to the non-creative forms of mental work as the predominant function of labor. Because of its definition, the service sector's lead is associated with a more heterogeneous situation. Here belong the remaining human physical work inputs—the classical 'services'—as well as the remaining non-creative mental work inputs, and, of course, the creative forms of mental work inputs whose share increases strongly.

[4] The fact is well documented for agriculture, where a direct comparison between 'primitive' methods of cultivation based exclusively on human energy inputs and modern methods based on non-human energy inputs is possible, see Pimentel and Pimentel (1996, Tables 10.3, 10.4, and 10.7). It is only in the last 20 years that the increase of the industrial energy coefficient has been stopped in the most-developed countries (see e.g. Gardner and Joutz, 1996).

the wage rate (on average, one hour of work buys an increasing amount of energy). As a consequence of the inflating energy utilization the current level of production and consumption rely on the depletion of the—finite—fossil energy sources. The mechanization in the transformation of materials did not only save labor in terms of hours worked per unit of output. It also meant a large-scale increase of output in terms of physical quantities, i.e. in the flows of *materials* processed in production. This would even be true with a non-increasing materials coefficient (materials per unit of output).

In part, these flows are necessary to maintain an ever growing stock of equipment (real capital which is, of course, nothing but arrangements of materials). In part, however, they also serve an increasing direct consumption of materials. This means that the consumptive act is a transformation of goods into waste, a dissipation of materials. Thus, while nature basically dissipates energy, the economic process dissipates both, energy and materials in ever larger quantities. Different from the highly sophisticated re-cycling of materials used within the dissipative system nature as a whole—where it is not extended by human intervention—the economic system puts only a negligible share of waste to use again; the lion's share is simply dumped (Faber et al., 1987). The obvious problem with this conduct is that, on one side, the stock of materials is slowly depleted while, on the other side, dissipated materials diffuse in the environment and strain nature's self-organization capacity. Different from the conventional theory of economic growth with its traditional interest in distribution conflicts between labor and capital, an approach that starts from the fact that the economy is a dissipative system ends up quite logically with emphasizing ecological features of the economic growth process. Obviously, in such a view, some concern about the long-term sustainability of economic production is justified.

4. Self-regulating and self-augmenting features in the economic process

Stylized descriptions of repeated regime switches in the historical process, including so-called stage theories, e.g. such as Fourastié's law, do not provide causal explanations for why those switches occur. The questions thus remain of what the driving forces behind the development are and what brings about the stated regularities. In order to prepare an explanation, some abstract hypotheses will be discussed in this section which characterize the economic process in very general terms as the result of a—societal—self-organization. An attempt will be made to identify self-regulating and self-augmenting features, the basic properties of a self-organizing process which have been mentioned in Section 1. An understanding of the interaction between self-regulating and self-augmenting tendencies should help to locate the driving forces of economic long-term development. However, an exploration of these two features is also of interest in itself as it helps to clarify the relevance of self-organization concepts for economic theorizing.

In Section 2Section 3 it has been argued that the modern economy is bound to operate within the natural constraints which any dissipative system has to face, and that these constraints suggest their own interpretation of economic production and growth. However, the economy is not organized, controlled, and developing according to the same principles and criteria as natural systems. In biophysical systems, for instance, the visible structure emerges from a cyclical organization of autocatalytic reactions (Eigen, 1971), which means that it is governed by a more or less complicated chain of chemical reactions. In the economic domain, by contrast, it is intelligent human action and imagination that drive the development, and these follow their own laws. In this section we will therefore turn to the question of whether a notion of—societal—self-organization is useful for explaining both the driving forces of, and the principles and criteria operating within, the economic process.

As has been mentioned in Section 1, self-organization can be interpreted as the interplay of self-regulating features and occasionally occurring self-augmenting features of a system. These features can indeed be identified in the operation of the economic system. There is the self-regulating price mechanism, based on an institutional set-up with binding budgetary constraints, on the one hand, and the self-augmenting effect of new knowledge emerging and diffusing in the economy on the other hand. Indeed, it will be claimed here that the driving forces of the economic process are to be found in the reasons which induce people to search for, to experiment with, and to implement new ways of action. One problem in developing the argument in more detail is the fact that, due to an heuristic bias, modern economic theory does not account equally for the two kinds of features of self-organization. While self-regulation is a core issue in the price-theoretic underpinnings of economics, the quasi-mechanical make-up of the predominant neoclassical approach impedes a proper understanding of the economy's self-augmenting features so that, until recently, they have gained little attention.[5]

The discovery of the self-regulating nature of the price mechanism was certainly a major intellectual achievement. When it has been stated above that the economic system is driven by human intelligent action and imagination, it is actually the possibly most disparate actions and intentions of a multitude of agents, who, in their partly competing and partly cooperating interactions, jointly determine the economic outcome. Given the complex determinants of individual action, which are difficult enough to understand in isolation, it is by no means a trivial claim that all the individual endeavors and ventures should result in a state of order, or coordination, provided the conditions of contractual freedom and legal certainty are met (in fact, as is well known, the idea has explicitly been rejected in the Marxist tradition). This is, of course, what the classical idea of the 'invisible hand' suggests: individual plans and actions, selfishly motivated as they may be, are spontaneously coordinated through the market process, i.e. in a way which is neither intentionally designed nor planned, so that they serve the common good.

As early as in Adam Smith's work, the idea has been given an expression in terms

[5] However, the recent upsurge of empirical and historical studies on the impact of technological innovations on the economy (Freeman, 1982; Dosi et al., 1988; Mokyr, 1990) reflects a growing awareness in the economic discipline of self-reinforcing features, accompanied by the rise of the evolutionary approach in economics.

of a theory of the market process (Smith, 1979, book 1, chap. 7). Smith saw the competing agents on the supply and demand sides inclined to enter, exit, or stay in the markets according to their individual opportunity cost calculations for which, he submitted, the agents would not have to know more than the relevant long-term average prices. In the short run, however, products and services have been prepared, and supply is therefore fairly inflexible. The competitive process yields market clearing 'actual prices' for each market in the short run. For reasons of random events, natural causes, or political intervention, these prices fluctuate endlessly around the (non-observable) 'natural price' in each market. This hypothetical price is determined by the long-term average opportunity costs of the suppliers and may, therefore, vary itself. The notion of short term price fluctuations around a hypothetical, moving equilibrium is not only quite complex, but also somewhat vague. Perhaps, it is best interpreted as simply expressing the idea of markets which have the capacity to negatively feed back to, or keep control of, any changes, leaving open whether the sources of change are exogenous or to be found within the market participants' opportunity cost perceptions.

Enthralled by the conviction that the time's ideal of science—Newtonian mechanics—provides an analogy on the basis of which the classics' conjecture can be given a more exact expression, the neoclassical writers reformulated price theory (Georgescu-Roegen, 1971, chap. 2). The idea was that in market disequilibrium (like in mechanical disequilibrium) there are forces present which, inducing and driving a process of convergence, eventually disappear in equilibrium. In the 'mechanics of utility and self-interest', as Jevons had put it, the force is a utility gain which can be realized by the market participants when adjusting towards a market equilibrium, a gain that does not vanish before the equilibrium is indeed attained. Self-regulation thus becomes a matter of the stability of adjustment processes. After an exogenous disturbance has occurred, the process is viewed as converging to a vector of unique and stable equilibrium prices. Since, by definition, a market equilibrium is a situation where all agents are assumed to realize their mutually compatible constrained maxima, a state of 'perfect coordination' is a state of rest. Should there be any further change (as it is in an evolving economy), it has to be exogenously caused change.

While such an implication of a mechanical adjustment makes sense for a set of scales and a weight that is thrown on one side of the scales, it induces misconceptions of what happens in markets. On the basis of general equilibrium theory there is no possibility of explaining the driving forces of economic development. To put it differently, when self-regulation is identified with the stability of a conservative system, like in classical mechanics, there is no way of entering self-augmenting features. As discussed elsewhere in more detail (Witt, 1985), in a changing environment, information processing problems on the part of the market participants usually prevent markets from reaching a state of 'perfect coordination'. What the market participants do know is the existence of an ultimate, though over time a changing, budget constraint as the cause of all opportunity costs. Furthermore, the agents are likely to know that there is a limit for the manipulation of their budget constraints through exchange over time: all prices have an upper bound, where demand is zero, and a lower bound, where the own costs of making an offer can no longer be covered. A living has to be made from exchanges at prices between the upper and the lower bound. Hence, for all agents in the economy there are viability bounds. Agents who do not manage to keep to these bounds over time do not survive economically. Losses and overdrawing of budgets alert the agents to the need to adjust their expenses and price and supply behavior appropriately. Since all the constraints are mutually imposed, the threat of being driven out of the market thus induces mutual coordination efforts.

The self-regulating capacity of the markets is thus maintained, although, in comparison to a fictitious, perfectly competitive world, not without some 'slack'. Only where no more 'fluctuations'—endogenously or exogenously caused—are present in the markets, and where all agents have time to learn about, and to make use of, every possible competitive edge—and thus erase it—would the upper and lower price bounds eventually collapse into unique, zero-profit, competitive prices in all markets. Then, and only then, perfect coordination would be reached. However, before this happens, the individual adjustments in a state of less than perfect coordination are likely to trigger a search for new ways of acting and the corresponding changes of behavior, i.e. endogenous change. It is an old insight that, if there is room to vary prices between upper and lower bounds without losing all of demand, then (monopolistic) profits can be realized (Arrow, 1959). When all market participants learn and adjust, upper and lower bounds tend to converge towards each other and profit opportunities dwindle. The market participants do not necessarily give in to that development and optimize on what is left to them as neoclassical theory has it. Actual behavior is richer. People who have been accustomed to earning profits are likely to look for ways that restore profit opportunities. When their aspirations are being frustrated many individuals are inclined to start searching for novel ways of acting, to experiment with, and try out, innovations rather than resigning themselves to their fate right away (for a more detailed discussion of the motivations for searching novelty see Witt, 1993).

In a self-organization perspective the point is crucial, since it explains how self-regulating features of the market process may turn into self-augmenting ones. If people are successful in their search for innovations, new profit opportunities (a corridor between upper and lower price bounds) are opened up through new knowledge. By way of imitation the new knowledge may diffuse through the economy so that new products, production technologies, and/or markets are formed (see Lesourne, 1992). This phenomenon is obviously not only the self-augmenting part of the self-organization of the economy, but, from the point of view of the market process, it also represents an endogenously caused de-coordinating effect. Innovations expand the innovator's viability bounds while contracting those of the innovator's competitors who, if they are for some reason or other prevented from imitation, may in turn start searching for novel ways of acting. Coordinating and de-coordinating tendencies in the markets, and the balance between them over time, usually do not allow but a 'viable coordination' to be reached.[6] This means that

[6] Witt (1985); for neoclassical equilibrium theory a structure like this is simply 'disequilibrium'. Hardly any concepts are offered to analyze what happens in disequilibrium. No wonder, thus, that neoclassical theory has difficulties in understanding how such a state 'far from equilibrium' could ever be persistent.

agents, by and large, manage to keep within the viability bounds, and, if they do, they may enjoy profit opportunities. Production, trading, and division of labor do take place, but the individual plans and imaginations are not perfectly compatible with each other. There are surprises, mis-allocations, backlashes, and losses that hurt. However, the threat of bankruptcy, by and large, disciplines all agents and enforces the self-regulating features in the market interactions which, as the classics conjectured, do exist.

5. A simple model of self-augmenting transitions

In order to be more specific with respect to what self-regulating and self-augmenting features in economic processes are, a simple model may be useful. Since there are many ways of putting the basic idea, the model to be discussed here is only one possible version of formalizing those crucial elements of self-organization. In Section 4 it has been argued that the concept of viable coordination—the notion of coordinating and de-coordinating tendencies coexisting in the market process—provides a key for understanding how the self-regulating features may turn into self-augmenting ones. Dwindling profits, or only a significant squeezing of the viability corridor, may trigger a search for novel ways of acting. The markets then change to the extent to which search for innovations cumulates and, eventually, succeeds. Some markets shrink or vanish, others are newly created and expand. Much of this story is well known from innovation research and the recently expanding evolutionary approach to economics which emphasize the role of novelty and its diffusion for understanding modern economies.

In evolutionary economics, like in the above discussion of the role of knowledge as a factor of production, focus is on the growth and generation of technological and scientific knowledge, that is knowledge about what can be technically realized. In the perspective of those people searching for new ways of acting that restore or improve the profitability of previous businesses it is, however, the guess of what will pay, rather than what can be done technically, that counts. The agents' searching and experimenting activities are thus directed at generating *economic* knowledge. Before new technological knowledge is transformed into valid economic knowledge many steps are usually necessary: technical adaptations to production conditions must be achieved, appropriate organizational set-ups must be figured out, calculation problems must be solved, reliable contractors must be found, the product market must be developed, etc. All this needs time; in fact, as reported for specific technologies (Usher, 1954; Mokyr, 1990), sometimes even quite a long time is required before what has been discovered as technologically feasible becomes an economic innovation.

The process of checking out those implications which are deemed economically most relevant is a gradual procedure. Vague hope in the prospects of a new production technology, based on a new input or a new combination process, or a technologically newly feasible array of products must grow into subjective confidence before a venture is undertaken on the new basis by the first innovators (and if hope fails to be strengthened there will be no innovation at all). Once, however, some pioneers have introduced the new processes or products, other agents may take this as an indication of promising economic prospects of the new technology so that their willingness to follow and imitate increases as the number of adopters increases. The verbal description of the process already points to a self-augmenting tendency that, after a kind of gestation period, may break up from what is initially only a vague searching activity.

In a simple way the process can be modeled as follows. Consider a market in which the prevailing production technology X is characterized by a certain dominant input. Assume a new technology Y, based on a different input, is being discovered in scientific and technological research. Economic agents who are inclined to search for innovative ways of acting because of frustrated aspirations or because they anticipate future frustrations start checking out possible economic implications of Y. Since this takes time, however, no implementations of the new technology in business ventures will initially be observed. In order to put this more formally, let the share, or relative frequency, of businesses using technology Y at time t be denoted by p_t. In the beginning, it is assumed, the old technology X, with a share $1-p_t$, prevails (i.e. $p_t=0$). In order to capture both notions, that of a frequency dependency effect governing imitation behavior and that of a gestation period, let us introduce:

Assumption 1: The probability of an economic agent of adopting technology Y at time t depends on the relative frequency with which Y has already been adopted by others at time t in such a way that it increases more than proportionately with growing p_t.

For ease of exposition a quadratic function will be used below to express the dependence. However, the basic argument works for a much larger class of more than linearly increasing monotonous functions.

Assumption 2: The probability according to assumption 1 is biased by a gestation parameter k_t. In the case that Y turns out to be economically more promising than X, k_t grows from -1 to $+1$ the faster, the more economically superior Y turns out to be to X. Otherwise $k_t=-1$ for all t.

A specification satisfying assumption 2 is, for instance

$$k_t = 1 - 2^{(1-\alpha t)} \tag{1}$$

where α, $0 \leq \alpha \leq 1$, is a parameter indicating the relative economic superiority of technology Y (the greater α, the greater is the economic advantage; if $\alpha=0$ there is no advantage).

Having in mind that the decision to actually adopt Y may be revised and that, for reasons of symmetry, assumptions 1 and 2 apply analogously for the decision to switch back to X, the randomly determined agent who makes up his mind in t may either be one who already uses Y or one who uses X. If, for convenience, it is assumed that agents line up in a random fashion in the time sequence in which they make their decisions concerning the adoption of Y, and that the population is large, the probability of finding an agent practicing Y (practicing X) in t is equal to p_t (to $1-p_t$). Under these assumptions, the relative frequency with which the new technology is present in the market develops over time according to the first-order difference equation

$$p_{t+1}=p_t+(1-p_t)p_t^2(1+k_t)-p_t(1-p_t)^2(1-k_t)=\rho_t \text{ for all } \rho_t\in[0,1]$$
$$p_{t+1}=0 \text{ for all } \rho_t<0, \text{ and } p_{t+1}=1 \text{ for all } \rho_t>1 \tag{2}$$

From Eq. (2) it can be seen that k_t has the effect of a weight that, in the beginning, i.e. for low values of k_t, discourages any decision to adopt Y. Only as confidence grows, i.e. for values of k_t approaching $+1$, does the adoption of Y become more likely; in fact, then it is strongly augmented by the frequency dependency effect.

Rearranging Eq. (2) yields within the constraints of the interval [0,1]

$$p_{t+1}=k_tp_t+(3-k_t)p_t^2-2p_t^3 \tag{3}$$

and the following can be shown:

Proposition: For k_t going from -1 to $+1$ as t grows during the gestation period the attractors of the process in Eq. (3) bifurcate.

Since the bifurcation is a well-known property of a first-order cubic difference equation like Eq. (3), a proof of the proposition is omitted. The bifurcation is, however, graphically displayed in Figs. 1–4. For $k_t=-1$ the globally stable attractor is $p^*=0$ (Fig. 1). As k_t grows another attractor occurs in $p^{**}=1$. The domain of attraction of the two—now locally stable—attractors is separated by the unstable fixed point $p^\circ(t)$ which moves down the 45° line towards p^* as k_t grows (Figs. 2 and 3). Once k_t approaches $+1$, p^* vanishes and gives way to a globally stable attractor p^{**} (Fig. 4). Using the specification in Eq. (1) for k_t in Eq. (3) the movement over time of the unstable fixed point p° on the 45° line can easily be calculated as being given by $p^\circ(t)=2^{-\alpha t}$.

What happens if the new technology Y indeed turns out to be superior to X with a growing positive economic knowledge about Y, i.e. with k_t growing over time e.g. according to Eq. (1)? For quite some time no change in the use of the technologies can be observed, although there is perhaps already considerable search and experimentation activity concerning Y under way. It is precisely this activity that can induce k_t to rise and, if this happens, prepares the ground for the transition to a self-augmenting phase of the process by causing the bifurcation. The bifurcation creates a new structure for the dynamics (its emergence is, therefore, considered the crucial element of self-organization in the sciences, see Haken, 1977). Once the separation point p° is close enough to the previously prevailing attractor p^* and is exceeded by some random fluctuation in, or historical circumstances inducing a shift of, p_t, the transition to Y as the prevailing technology is an almost inevitable process (self-) augmented by the frequency dependency effect. The same holds by necessity once p^* vanishes for large enough k_t.

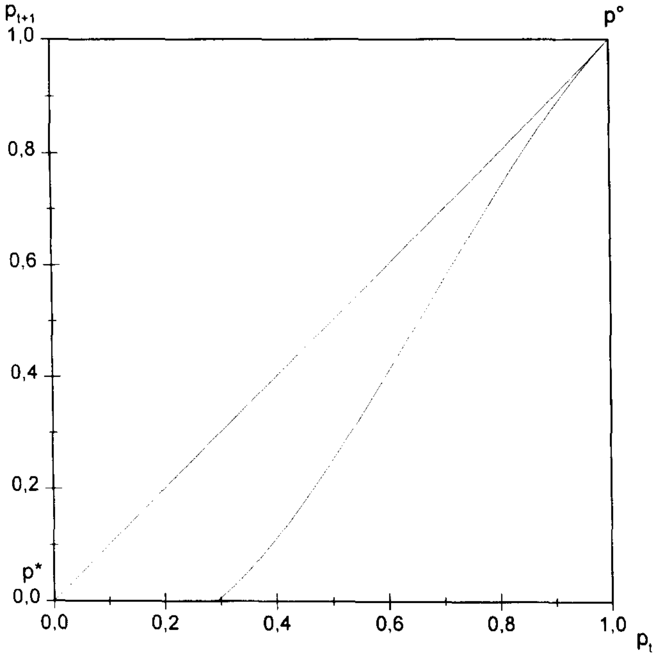

Fig. 1. Attractors of the adoption process for $k = -1$.

If the gestation period is long, i.e. if, in the specification in Eq. (1), α is very small, $p^{\circ}(t)$ changes its position slowly. In fact, the change may be so slow that it appears negligible compared to the changes occurring in $p(t)$ after the separation point has been exceeded. As can be collected from the shape of the graph of Eq. (3), to the right of a given p° in Figs. 2–4 the difference $p_{t+1} - p_t$ first increases and then decreases once p^{**} wins through against p^* and attracts the process. This implies an s-shaped growth path for the relative frequency p_t of the new technology Y as is well known from diffusion research. As experience has taught, it is quite likely that yet another new technology based on a different dominant input appears and possibly invades the market at some time later. If this new technology is labeled Z, it may play a similar role relative to Y as Y has done relative to X. Thus, after some while p_t is likely to start declining as $1 - p_t$ has declined before. The bifurcation and the subsequent self-augmenting transition repeats itself.

Take, for example, the different primary energy sources wood, coal, oil, gas, nuclear power, and solar insulation as the dominant input characterizing a technology. As has been shown by Marchetti (1980), the sequence in which they gained a relative dominance in market penetration may indeed be considered a case of sequential regime shifts accompanied by the corresponding diffusion processes as described by the above model. Economic self-organization then not only appears as an interaction of self-stabilizing and self-augmenting features as submitted; it also suggests itself as a guiding principle of the way in which man has succeeded to extend nature's self-organization.

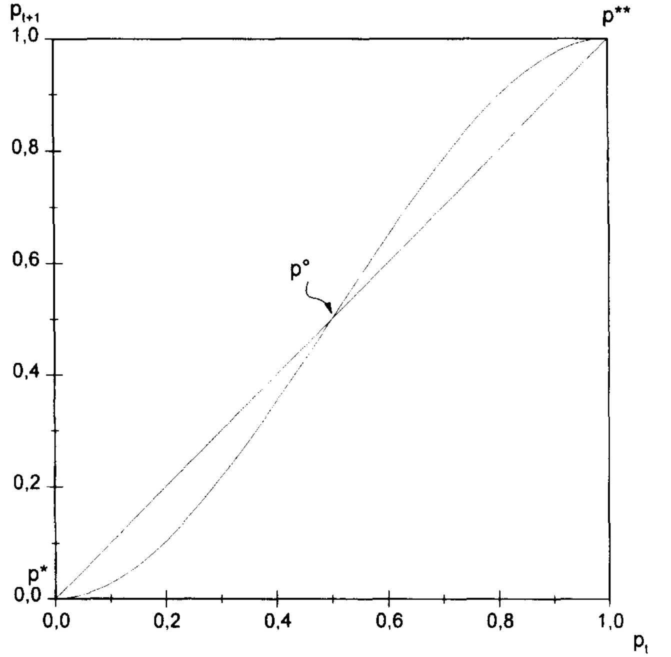

Fig. 2. Attractors of the adoption process for $k=0$.

6. Conclusions

Inspired by the newly emerging 'self-organization' paradigm in the bio-sciences, the present discussion revolved around two questions: does self-organization play a role in the domain of economics and if so, do concepts associated with the notion of self-organization in the sciences offer new insights for economic theory? The answers that have been suggested point to a rather mixed picture when it comes to assess the relevance of the new development in the bio-sciences for economics. On the one hand, the modern economy obviously is a dissipative system and, insofar, shares many features with natural dissipative systems. The economic theory of production and growth is, presumably for historical reasons, in a shape that makes it difficult to see how strongly the dissipative system economy hinges on means provided by nature. Insights in the basic modes of nature's 'production' may, therefore, be helpful in improving our understanding of how human long-term economic development could be achieved.

On the other hand, the ways in which the dissipative system economy is organized and develops over time differ crucially from self-organization in nature. It is intelligent human action, imagination, and a growing knowledge that support the process. The collective outcome of individual intelligent activities depends, of course, on the partly competing, partly cooperating interactions of the multitude of agents. This very fact explains the economists' interest in the coordination problem since the

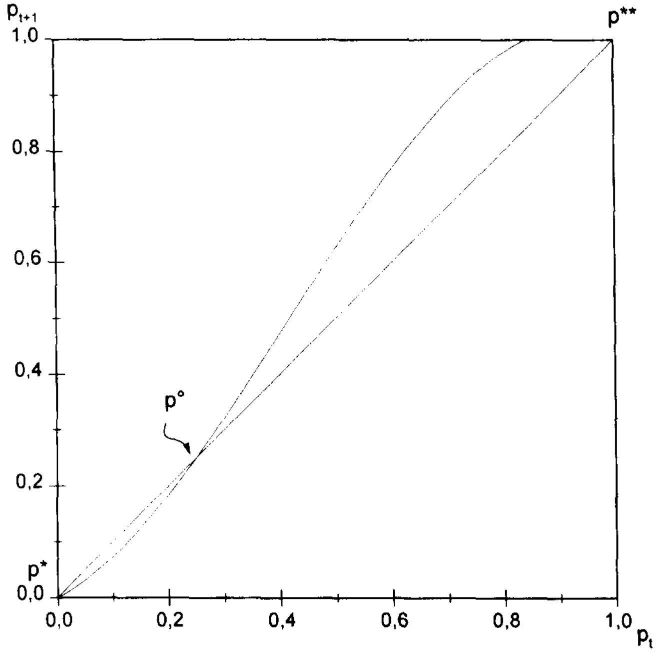

Fig. 3. Attractors of the adoption process for $k=\frac{1}{2}$.

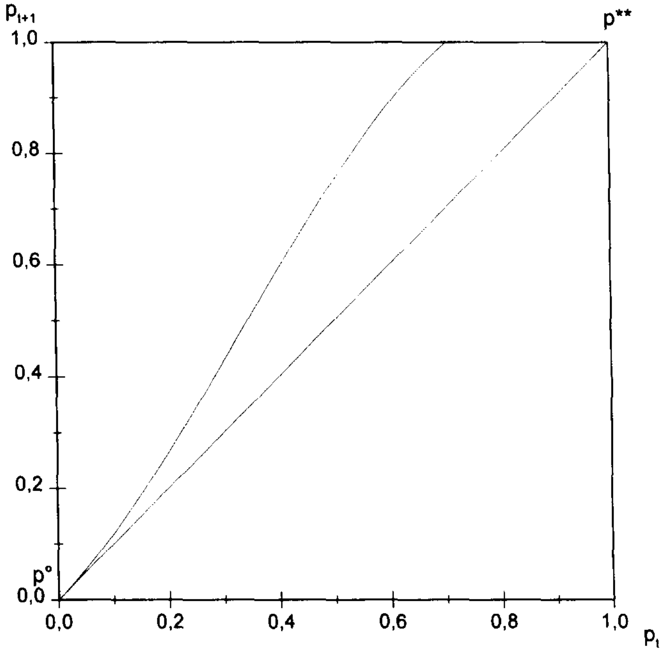

Fig. 4. Attractors of the adoption process for $k=1$.

classics. It has induced what may be considered a genuinely economic theory of a self-organization process which, in recognizing the self-regulation capacity of the system of markets, anticipates an important feature of the modern self-organization paradigm. However, as can be learned from the latter, self-regulation capacities are not all of the story. There is an important other part to which the notion of self-organization draws attention: the temporarily self-augmenting (or self-de-stabilizing) processes. Indeed, these temporarily self-augmenting phases of the economic process seem to be crucial for understanding the driving forces behind economic growth. This is difficult to explain if economic self-organization is too narrowly couched in terms of equilibrium economics, i.e. in a view that identifies the self-regulating capacity of the price mechanism with the attainment of perfect coordination.

As an alternative, a theory of 'viable' coordination has been suggested. In such an interpretation there is room for explaining how the individuals' motivation to search for, and experiment with, new economic knowledge and to implement it in innovative action drive the development and can give rise to self-augmenting features. The causes that trigger the search for innovations have been identified, in this abstract framework, in the frustration of individual aspiration levels. Such a frustration, it has been argued, results regularly through the squeezing of the individuals' viability corridor. Search of this kind allows knowledge to be created and grow about new ways of producing and doing the business. As has been outlined in this paper, the collective features of such individual economic search processes may generate the temporarily self-augmenting tendencies that induce a transition from one locally stable, and only transiently prevailing, attractor (configuration of economic activities) to another. In some cases, such a transition may amount to no less than the regime switches in the utilization of energy and materials which seem to be so characteristic for the man-made extension of nature's self-organization in long-term economic growth.

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