Time Irreversibility in Economic Theory: A Conceptual Discussion*

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This paper tries to clarify the role time irreversibility plays in several areas of economics. To this end three types of time irreversibility and several conceptual elements of economic analysis are introduced such as Boundary Conditions, Objectives, Procedural Rationality. These are used to typify various economic schools of thought and to examine the roles of time irreversibility in the various schools. Some of these conceptual elements are then combined to give a framework for the analysis of long-term economic development, involving invention, production and interactions with the environment.

I. Introduction

In this paper we shall attempt to contribute to the clarification of the role time irreversibility plays in several areas of economic analysis. Although economists have developed several dynamic approaches it is well known that problems of time are not a main area of research, as for example in physics. This can be observed by the circumstances that temporal structures of consumption and production and in particular time irreversibility were by and large not in the past, and are not in the present, main issues of economic discussion. Similar statements hold for the teaching at colleges and universities: The foundations of economics are taught in microeconomic and macroeconomic courses, where dynamics and aspects of time generally are only of secondary importance. The same holds for much of the teaching of general equilibrium analysis.

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In this paper we have two aims. First, we want to give a short overview of how time irreversibility has been dealt with by various economic schools. Because of the lack of space, our representation runs the risk of not doing justice to the different approaches. Second, on the basis of these considerations we shall outline a framework for the analysis of long-term development, involving invention, production and interaction with the environment, which explicitly takes care of time irreversibility (Faber and Proops 1985, 1986). Our particular attention will be on the development of physical, environmental and economic boundary conditions. This discussion will continue our earlier joint work (Faber and Proops 1985, 1986).

In Section II we make some references to various aspects of time which have been treated in the literature. Thereafter we introduce three types of time irreversibility. In Section III we shall give a conceptual structure for economic theorizing by describing conceptual elements, all of which are used in the literature. These elements are then taken in various combinations to typify several schools of thought in economics. Thereafter we attempt to synthesize and supplement these characterizations, and to explore how aspects of time irreversibility are used in economic theorizing. While in Section III we will deal mainly with short-and medium-run aspects, in Section IV we turn to the long-run development of economic activity and discuss how market failures are of particular importance in the long-run and lead to certain time irreversibilities. The insufficiencies of existing environmental resource models to capture these time irreversibilities lead us to propose a conceptual framework which is more suitable to examine the historical experience of the relationship between economic activities and the temporal development of the physical limits in the environment, and to show how production, innovation, physical limits of the environment, and invention interact with each other. In Section V we acknowledge ambiguities of our approach as thus far formulated, and put forward a programme for future study.

II. Notions of Time

A. On Concepts of Time in Economic Theory

Before proceeding we refer to the literature to give examples to indicate various ways in which time is used in economics.

The notions of statics, comparative statics and dynamics form the triad familiar to every student of economics (see e.g. Samuelson 1947). While the first two of these have clear cut meanings, the last one has many aspects. Hicks (1939, 1946, p. 115) defines: "I call··· economic dynamics those parts where every quantity must be dated". Hicks' (1939, 1946, pp. 126–7) central notions in his dynamic analysis are:

> ···the week, the plan, the definite expectations··· by employing them we do a certain amount of violence to the phenomena of the actual world, but not more than necessary, if we are to make any headway in dynamic theory.

Samuelson (1947, p. 315) distinguishes between "dynamic and causal (nonhistorical)" and "dynamic and historical", a distinction used by Schumpeter (1954, p. 965 fn. 5):

> It should be pointed out explicitly that, as defined, dynamic theory in itself has nothing to do with historical analysis: Its time subscripts do not refer to historical time–the simple model we used as an example tells us nothing about whether that demand–supply configuration obtained in the times of President Washington or of President Roosevelt; and its sequences are theoretical and not historical or, as we may also put it, it uses theoretical and not historical datings (see also Georgescu–Roegen 1971, p. 136).

Further, Samuelson (1947, p. 315) notes that:

> ···a truly dynamical system may be completely nonhistorical or causal, in the sense that its behavior depends only upon its initial conditions and the time which has elapsed, the calendar date not entering into the process. For many purposes, it is necessary to work with systems which are both historical and dynamical. The impact of technological change upon the economic system is a case in point. Technological change may be taken as a historical datum, to which the economic system reacts noninstantaneously or in a dynamic fashion.

In analysing dynamic systems Samuelson (1947, Part II, see in particular, pp. 260–9) is mainly interested in stability problems.

In the literature of modern intertemporal equilibrium theory, essential targets of analysis are the question (1) how can the concept of efficiency be extended to the long–run (see Cass 1972); (2) can intertemporal efficient development be achieved by the market mechanism (Kurz and Starret 1970).

Finally we mention Boland's (1978, p. 240) study of the "Hayek Problem":

> …as Hayek recognised many years ago, how time is treated is an important aspect of any explanation of historical change. It is the main purpose of (Boland's – the authors) paper to offer a solution to the "Hayek Problem": How can we explain the process of change in economics and remain consistent with the principles of (individual) rational decision-making? The present solution proposes a dynamic concept of knowledge in which learning is a real-time (irreversible) process.

We agree with Boland that the irreversible process of learning is of great importance to the understanding of economics, but we feel that there are also other concepts of irreversibility to be taken into account.

B. Concepts of Time Irreversibility

The "historical time" to which Samuelson refers requires the explicit recognition of the different statuses of the past and the future, the asymmetry of time. Common experience tells us that the past is unambiguous (though not necessarily known in all detail), while the future is ambiguous in many respects. We usually recognize this in economics by refering to "Risk" and "Uncertainty" being associated with future states of the world.

The asymmetrical nature of time has long been recognized in the natural sciences through the "Two Arrows of Time". The First Arrow of Time refers to the tendency over time of natural systems to disorder (under certain circumstances); this notion is summarized in the Second Law of Thermodynamics, the Entropy Law (Georgescu-Roegen 1971). The Second Arrow of Time reflects the tendency over time of certain systems towards greater organization and complexity; this cannot be summarized in a simple thermodynamic law, but the physical principles involved have been explored in detail by Prigogine[1] and his school (see Prigogine and Stengers 1984).

In Neoclassical economics the asymmetry of time has not been a central issue, and so has received relatively little attention, with this being mainly in production theory. In particular Koopmans' (1951, pp. 48–51) axiom that the production process is irreversible, meaning that inputs cannot be produced from outputs, is an explicit recognition of the operation of the Second Law of Thermodynamics in production (see also Debreu 1959, pp. 39–42). However, the majority of Neoclassical theorizing and modelling does not explicitly

[1] A short summary of the physical implications of the Two Arrows of Time is given in Faber and Proops (1986, pp.304–6).

deal with the asymmetry of the past and future, and the irreversibility of processes in time (see Stephan 1987, Chapter 2). In contrast, the time irreversibility of investment processes is a central feature of the Evolutionary and Austrian schools of thought, although in our view a detailed analysis of the full implications of time irreversibility for economic analysis has not yet been satisfactorily completed.

A necessary precondition of such a detailed analysis is the description and classification of the types of time irreversibility that can be identified. Towards this end we have tentatively identified three types of time irreversibility which are important in economic analysis (Faber and Proops 1986, pp. 296–303):

Risk — Irreversible Time 1

> The future and the past are treated asymmetrically because of asymmetric information structures, i.e. past events are known and therefore certain; Future events are not known for sure, but can be associated with known objective or subjective probability distributions based on knowledge of the past.

Uncertainty — Irreversible Time 2

> The future may contain novelty that is definitely unknowable, i.e. some future events cannot be associated with probability distributions based on knowledge of the past.

Teleological Sequence — Irreversible Time 3

> Particular goals often require economic developments or particular temporal sequence of decisions and actions; this phenomenon has two aspects: (1) On the primal, technologies and production structures have to be provided in a temporal order, in particular. (2) On the dual, this sequence of actions implies a sequence of prices (e.g. a discrete cobweb model defines a price path to its equilibrium which embodies the history of its evolution). Usually capital goods have first to be provided before consumption goods can be produced.[2]

[2] Economic activities are directed towards a definite end (Greek: telos) which, however, cannot be attained directly since production takes time, as is stressed in Austrian capital theory.

III. Conceptual Structures of Economic Schools of Thought in the Short- and Medium-run

A. Conceptual Elements for Economic Theorizing

We wish first to identify eight conceptual elements for use as "building blocks" in characterizing various economic schools of thought. These are:

A: Objectives

The objectives can be individual or collective.

B: Theories of the World

Any decision-making individual or organization uses, explicitly or implicitly, theories about features of the world relevant to their objectives.

C: Boundary Conditions

This constitutes: (C1) physically determined limits in term of the state of the environment and resources; (C2) socially determined limits in terms of the political system, the economic system (e.g. market, planned, etc.), the legal famework, economic institutions, market structure, preferences, technology; (C3) economically determined limits, such as the stocks of intermediate factors and capital goods, and prices if a price guided economy is given. There are great differences in how each of these limits can be changed over time. In addition, in general it takes more time to alter physical (C1) and social (C2) than economic limits (C3). The possibility for adjustment and the duration of the adjustment paths strongly depend on the time irreversibilities defined in Section II. Of course there exist interrelationships between the three kinds of limits, i.e. an increase in the stock of capital goods (C3) will in general decrease the amounts of resources in the environment (C1).

D: Procedural Rationality

Following Simon (1967), we distinguish between "substantive rationality" and "procedural rationality". Substantive rationality requires that the economic actor has a well-defined objective and a set of boundary conditions; the process of choice corresponds to achieving a global optimum. In contrast, procedural rationality is much weaker; it suggests only that the choice process is undertaken systematically, for example, by using "rules of thumb".

E: Computational Capacity

Again following Simon (1972), it is necessary to recognize that even well-defined objectives, boundary conditions and procedural rationality may give rise to problems for which optimizing solutions make great computational demands. The capacity of an economic agent to solve such problems will be limited and may therefore be a binding constraint upon his decision making.[3]

F: Decision

On the basis of his state of knowledge, as embodied in elements Objectives (A), Theories of the World (B), Boundary Conditions (C), Procedural Rationality (D) and Computational Capacity (E), the economic agent reaches a decision.

G: Implementation

The reaching of a decision leads to its implementation.[4]

H: Coordination

The implementations by the economic agents give rise to a coordination process e.g. coordination through markets. Each of the conceptual elements A to H has various aspects of time associated with it. The exact involvement of time in these elements varies between economic schools of thought.

B. Typifying Economic Schools of Thought

In this section we shall sketch, without demand of completeness, how various economic schools of thought deal with these all of these conceptual elements. The schools of thought to be examined have different emphases; they, therefore, have both different combinations of these elements and also give different interpretations to the elements used. In particular, for some schools of thought Boundary

[3] Because of its importance we have Computational Capacity (E) not subsumed under Boundary Conditions (C) but listed separately.

[4] Not implementing a new production process may be the result of decision if the currently used process is optimal.

Conditions (C) may reflect either strictly economic limits (C3), while for others it invokes economic (C3) and social limits (C2).

In this section we shall concern ourselves with typifications concerning the short- and medium-run models involving resource depletion and environmental degradation. Rather than pointing out weaknesses, we shall try to show the strength of each approach. This evaluation will give us hints as to how the different schools of thought may contribute to an encompassing conceptual structure for economic analysis. In particular, by exploring the role time plays in the conceptual elements, and their interrelationships, as utilized by the various schools of thought we aim to show that time, and in particular time irreversibility, plays an essential role in a wider conceptual structure.

A) The Neoclassical Approach

With regard to the Neoclassical approach in economics, we wish to distinguish between the explicitly "equilibrium" models, where adjustment to equilibrium is taken to be sufficiently rapid, so that only descriptions of the equilibrium state are important, and "disequilibrium" models, where non-equilibrium activity is important.

Equilibrium models of a static, comparative static, temporary, intertemporal and also a stochastic nature have the following general conceptual structure:

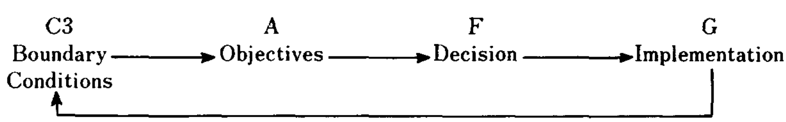

FIGURE 1

The meaning of the first three arrows in Figure 1 are straight forward; the last one indicates that the Implementation (G) leads to a change in economic characteristics for the Boundary Conditions (C3), such as the stocks of intermediate factors and of capital goods. Theories of the World (B) are not an issue, except in Rational Expectations models, where it is taken as given.

It is generally assumed in this case that Procedural Rationality (D) is identical with Substantive Rationality; the meaning of the term "rationality", as generally used in Neoclassical economics, is identical with Simon's notion of Substantive Rationality, mentioned above.

Computational Capacity (E) has not been an issue[5]; it is assumed always to be sufficient to solve the optimization problem that arises. Coordination (H) is assumed to be organized by a fictional auctioneer.

Only those equilibrium models with stochastic elements invoke the asymmetry of time; they then exhibit Time Irreversibility 1 (Risk).

In general, for "equilibrium" models the steady state attained is independent of the path taken towards it,[6] while for "disequilibrium" models the steady state attained will, in general, depend upon the path taken (see e.g. Fisher 1981). For "equilibrium" models the problem of market coordination becomes the tatônnement process through the auctioneer; in contrast to this, for "disequilibrium" models coordination is an important issue.

Disequilibrium models can be represented by:

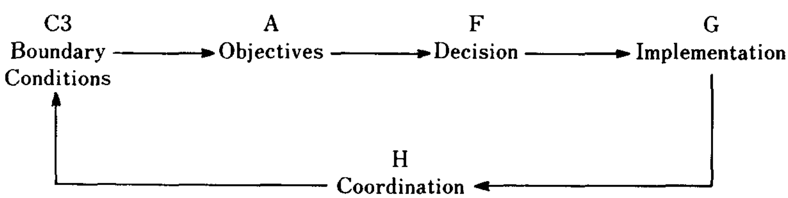

FIGURE 2

Disequilibrium models may also be stochastic and therefore exhibit Time Irreversibility 1 (Risk).

More interestingly, the time structure of the non-equilibrium trading will generally generate a "ratchet" effect on prices. In this sense it exhibits Time Irreversibility 3 (Teleological Sequence). For example, a Samuelson-Hicks trade-cycle model can define a path towards its steady state that embodies the "history" of the path in its evolution. That is, starting from given initial (boundary) conditions, the adjustment mechanism generates a path from the "past" to the "future".

B) Neo-Austrian Capital Theory

The structuring of the conceptual elements is the same as for

[5] The development of computable equilibrium models, however, shows that there exists a serious problem because of dimensionality. At the present state of the art, models with only few equations and prices can be solved (Manne 1985; Stephan 1987).

[6] See Mirowski (1984) on the problem of path independence in Neoclassical models.

equilibrium models in Neoclassical analysis (Figure 1). However, the focus of Neo-Austrian capital theory is on Implementation (G). In particular, concentration is given to the process of accumulation of a stock of heterogeneous capital goods to allow the production of consumption goods and the innovation of techniques.[7]

The process of production and thence accumulation of capital goods also exhibits a "ratchet" effect. For example, the production of consumption goods requires the previous production of capital goods. This implies that Implementation (G) invokes Time Irreversibility 3 (Teleological Sequence).

C) The Post-Keynesians

The Post-Keynesian literature is very diverse in its concerns. Boundary Conditions are seen in terms of both economic (C3) and legal, institutional and market structures (C2). The Objectives (A) are more of a collective than of an individual nature, and do not seem to us a central issue for this school of thought. Generally, the problem of optimization is not in the forefront of the analysis, hence the issues of Procedural Rationality (D) versus Substantive Rationality, and of Computational Capacity (E) are little addressed. However, Decision (F) and Implementation (G) are involved by Post-Keynesians; the issues approached with these elements concern, *inter alia*, savings, investment, and wages. The central Post-Keynesian concerns are unemployment and relative factor rewards, which are an outcome of the market Coordination (H) process.

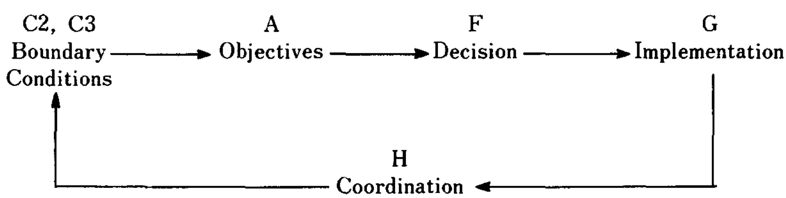

FIGURE 3

The Coordination problem is seen as involving aspects of both Risk (Time Irreversibility 1) and, in a less well-defined way, Uncertainty (Time Irreversibility 2).

[7] For a review of Neo-Austrian capital theory, see Faber (1986, pp. 20-31).

D) Evolutionary Economics

Evolutionary economics is centrally concerned with the process of learning and adaptation; thus the process of formulation and revision of Theories of the World (B) is an important issue. Another area of major concern is Coordination (H) of market processes. Evolutionary economics does not make the assumption that the decision process is Substantively Rational; instead Procedural Rationality (D) is given prominence, particularly with regard to the role of "rules of thumb". Boundary Conditions (B) are seen in terms of both economic (C3) and social (C2) limits. Computational Capacity (E) is often seen as limited, and hence appears as an issue here.

Evolutionary economics is still a young discipline and consequently diverse in its concerns and its procedures (see Nelson and Winter 1982; Witt and Perske 1982; Cross 1983; Witt 1987). It should be noted, therefore, that formal models in this area generally involve only some of the conceptual elements shown below in Figure 4.

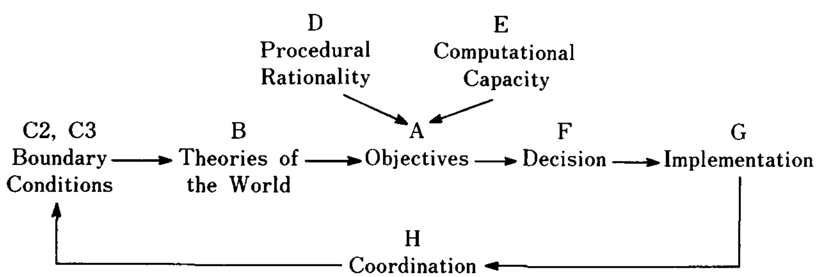

FIGURE 4

Risk (Time Irreversibility 1) is frequently explicitly recognized in the Boundary Conditions (C2, C3). Uncertainty (Time Irreversibility 2) of the Boundary Conditions is also often invoked; in particular the emergence of novelty through invention and innovation are frequently discussed. In the human capital approach the process of learning has been regarded as akin to capital accumulation; this indicates that the learning process exhibits Time Irreversibility 3 (Teleological Sequence).

E) The Austrian Subjectivist School

In terms of its conceptual elements involved, these are similar to those of Evolutionary economics; this reflects their sharing of some intellectual ancestry (Witt 1987, pp. 31–77). However, while the Evolutionary school uses many of the methods and techniques of Neoclassical economics, Austrian Subjectivism rejects formal modelling in favour of a more verbal, open model of discourse. Moreover, it has distinguished itself strictly from both the Neoclassical and Keynesian schools, particularly through its emphasis on the role of the individual decision maker in the face of radical uncertainty and ignorance (for a fuller discussion, see Pellengahr 1986).

Because the Austrian Subjectivists employ a rather open, verbal approach which is not directed at prediction, they are able to encompass all three types of Time Irreversibility, although only in a loose fashion.

C. Preliminary Conclusions

While the Neoclassical approach offers methods for the production of operational results in terms of "logical time", aspects of "historical time" are only considered to a relatively small extent. This implies that important economic and social questions cannot be dealt with in "…a single monolithic model for all reasons" (Solow 1985, p. 330). The converse holds for Austrian Subjectivists, who have an all-encompassing view of real time; however they can offer only few operational results.

We do not feel that this apparent trade-off between operationalism and the comprehensive involvement of time irreversibility is necessary. Indeed, the recent emergence of Evolutionary economics raises hopes that it may be possible that some of the powerful formal methods of Neoclassical economics can be used to address the wider issues encompassed by Austrian Subjectivism. To this end we shall consider once again the eight conceptual elements presented in Figure 4. Indeed, it is obvious that this diagram implies a certain real-time structure. The Objectives (A), the Theories of the World (B), the Boundary Conditions (C), Procedural Rationality (D) and Computational Capacity (E) will create within some period of time a Decision (F). This in due course will give rise to Implementation (G) in another period, and thereafter to a process of Coordination (H), which in turn affects the Boundary Conditions (C); thus a new decision becomes required, and in turn must be implemented, etc. As the rate of change of many economic aspects of the Boundary Conditions (C1) are likely to be reasonably rapid in reality, and as the Computational Capacity (E) is often restricted, it is unlikely that any Procedurally Rational decision process will also be Substantively Rational (i.e. optimizing).

IV. The Temporal Development of Boundary Conditions in the Long-run: Physical Limits in the Environment

We now turn to long-run aspects and concentrate on the temporal development of the physical limits, i.e. of the Boundary Conditions (C1). In the following Section *A*, we shall discuss how long-run environmental resource problems have been examined within Neoclassical and Neo-Austrian frameworks. In Section *B*, we apply some of our conceptual elements to historical experience.

A. Typifying Long-Run Resource and Environmental Models

A) Neoclassical Models with Backstop Technology

A typical Neoclassical resource model involves a given resource stock and a given set of techniques, which are either fully known, or at worst Risky (Time Irreversibility 1). The operation of the model would indicate how optimal resource depletion leads to relative factor and resource price changes, giving rise to factor substitution through the innovation of new techniques. Price changes under the assumption of perfect future's markets implies that the notion of market Coordination (H) is not an essential issue here. To cope with the possibility of an infinite time horizon it is generally assumed that there is a "Backstop" technology available, which utilizes at high cost an unlimited or renewable resource (see e.g. Dasgupta and Heal 1979, pp. 175–8). The conceptual elements in such a model are those already shown in Figure 1, except that the focus of Boundary Conditions is upon physical limits (C1) rather than economic limits (C3).

It is apparent that such Neoclassical models are special forms of the intertemporal equilibrium approach and therefore can only exhibit Time Irreversibility 1.

B) Neo-Austrian Models of Resource Use

The conceptual elements involved are the same as for the Neoclassical models above. However, particular attention is paid to Implementation (G). This is due to the emphasis on what Hicks (1965 Chapter 7, 1973) called the "traverse". Once a new technique has been innovated in response to technical progress and relative prices, there remains the problem of how such a new technique becomes embedded in the wider production process. For example, the innovation of microelectronic components over the past decade has had profound implications in many industries other than electronics. The entire technology of the economy is forced to undergo realignment because of a change of technique in only one sector. This realignment of production due to resource and environmental constraints within an economy reflects Time Irreversibility 3 (Teleological Sequence) (see Faber, Niemes, and Stephan 1987, Chapter 6).

C) Market Failures in the Long-Run

Using a Neoclassical or Neo-Austrian approach one can show that under competitive conditions the price of a resource is equal to its marginal cost of extraction plus an economic rent (royalty) (Dasgupta and Heal 1979, pp. 167-18). The royalty is the opportunity cost that the resource is used now and not later. It therefore is an indicator of the substitution costs which occur when switching to another resource. This indicator, in the form of the royalty, is expressed in present values, which is achieved by discounting spot market prices. Because of Risk (Time Irreversibility 1) and Uncertainty (Time Irreversibility 2), the discount rate is generally so high that the royalty tends to be low. This in turn evokes a high use of resources.

It can be further shown that at the optimum of an economy, the price of a commodity should not only be equal to its marginal production costs, including the royalties of the various resources used in its production, but should contain in addition its environmental costs (Faber, Niemes, and Stephan 1987, Chapter 7). Because of their intertemporally external nature, not only within one country but also between countries, these are not reflected in competitive market prices. It is well known how difficult it is to enact environmental legislation on a national, and in particular on an international level, to take care of these environmental costs. Even if this is done, for the same reason as mentioned above we encounter still the problems connected with a high discount rate; it follows, therefore, that in reality the intertemporal negative external effects are accounted for only insufficiently.[8]

[8] We note in passing that the existence of future's markets for resources and for rights for environmental pollution could take care of these effects. In reality, however, very

From these considerations we conclude that the lack of inclusion of intertemporal external effects (concerning resources and environment), by markets, cause the actual market prices of goods to be so low that they do not adequately reflect the intertemporal substitution and environmental costs they incur. This in turn leads to the Implementation (G) of techniques using high amounts of resources and effecting increasing environmental degradation. This, however, implies that the physical Boundary Conditions (C1) are approached quickly. This leads to Time Irreversibility 1 (Risk) and Time Irreversibility 3 (Teleological Sequence), since the entropy of the earth increases (see Faber, Niemes, and Stephan 1987, Chapters 3 and 4), and also to Time Irreversibility 2 (Uncertainty) because one does not often know the effects of approaching the physical limits. An example of such uncertainty is the current concern about the effect of fluorocarbons on the ozone layer (for a more detailed discussion of this general area, see Faber and Proops 1985, 1986).

B. Conceptual Elements of Long-run Economic Development

It is apparent that essential aspects of Time Irreversibility are not captured by the Neoclassical and Neo-Austrian environmental resource models. We therefore wish to propose a more encompassing framework, which enables us to relate our conceptual elements to the historical experience of the relationships between economic activity and the natural world. We shall stress in particular the relationships between physical limits, invention, innovation and production. By doing this we want to recognize more explicitly the asymmetry of time. This analysis will be of a long-run and highly aggregated character. To this end we follow Koopmans' (1974, pp. 327–8) comment that:

> In a world of continuing but only dimly foreseeable change in technology and preferences (that means in our terminology in Boundary Conditions (C) – the authors), the notion of equilibrium disappears, but that of an adjustment process remains.

This implies that for the analysis of long-run developments one does not need to focus upon individual decision making, which is of central importance for General Equilibrium Theory; hence we shall

often future's markets of dated commodities do not exist or are thin. The assumption of a complete set of future's markets leads to all sorts of difficulties, e.g. the legal enforceability of a contract for the delivery of a thousand barrels of Middle East oil ten or fifty years from now (Manne 1985; Faber and Wagenhals 1986).

not be concerned with the following conceptual elements: Objectives (A), Procedural Rationality (D), Computational Capacity (E) and Decision (F).

We retain the other four elements (C, B, G and H). Of central importance are the Boundary Conditions (C); Of these we particularly consider their physical aspects, i.e. the environment as a supplier of resources, as a supplier of public goods, and as a recipient and transformer of waste products.

The Implementation (G) of production activities will, in the long-run, lead to the depletion of resources and the generation of pollution. This in turn will cause physical limits to become increasingly binding constraints upon economic activity. First, the price mechanism of the Coordination (H) element will cause substitution of factors of production, in particular of resource use, thereby possibly generating a more rapid rate of innovation of less resource-intensive and of less pollution-intensive techniques.[9]

The more closely are the physical limits approached, the greater will be the pressure on society, via increasing prices, to find new techniques of production. We recognize, of course, that the price mechanism is only one source of invention. Since invention is of extreme importance in the long-run, we retain the element Theories of the World (B) as the means by which inventions are generated.

The interrelationships between the four elements mentioned above, are shown in Figure 5, which we shall explain now in detail. We start with the Implementation (G) of the production process, which uses resources and generates pollution. This will directly affect the physical limits (C1) experienced by the economy. As we argued in Section IV. *A.C)* above, the corresponding intertemporal external effects because of the use of depletable resources and because of pollution are not adequately reflected by the Coordination H, be it a market or a planning agency. This relationship is indicated by the arrows passing from G to C1. The increasing resource shortages, in turn, will generate relative price changes (arrow from C1 to H). This will lead to the innovation of previously available, but unused techniques (arrow from H to G). In addition, however, the increased relative prices of resource will lead to research towards inventing new techniques which are resource saving, or allow the substituttion of other less costly resources (arrow from

[9] We recognise that there we have given Coordination (H) only a limited role in this long-run conceptualization. For an wider examination of the role of Coordination in long-run economic development, see Braudel (1985).

H to B). Besides this price induced invention there will be also to a considerable extent non-price induced research aimed at ameliorating the environmental effects of economic activity (arrow from C1 to B).

The invention of new techniques will allow their innovation in the production process (arrow from B to G).

In parentheses we note in Figure 5 those aspects of each element upon which we have focussed attention. We further indicate by the numbers 1, 2 and 3 which types of Time Irreversibility we consider to be involved in each conceptual element. With regard to these types of Time Irreversibility in Figure 5 we remark:

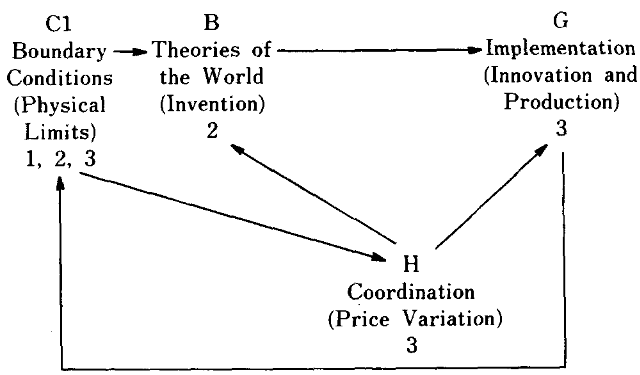

FIGURE 5

a) Time Irreversibility 2 (Uncertainty) noted for Theories of the World (B) (Invention) reflects the uncertainty about the inventive process. By their nature, inventions cannot be predicted in the sense of Risk.

b) Implementation (G) (Innovation and Production) is associated with Time Irreversibility 3 (Teleological Sequence) through the assumption of the most general form of capital accumulation and production, as described in Section III. *B. B)*.

c) Coordination (H) (Price Variation) is a process which invokes Time Irreversibility 3 (Teleological Sequence) because of the general assumption of disequilibrium trading (we here eschew the general equilibrium approach), as discussed in Section III. *B. A)*.

d) Bøundary Conditions (C1)(physical limits) invoke all three types of Time Irreversibility. Time Irreversibilities 1 and 3 can be associated with the second law of Thermodynamics (the Entropy Law, see Faber and Proops 1986, p. 306). The use of natural resource and the generation of pollution will increase the entropy of the natural environment and thus tighten the physical limits imposed upon the economy. Time Irreversibility 2 reflects the increasing Uncertainty about the state of the natural world brought about by resource use and pollution; This has been discussed in more detail in Section IV. *A. C)* above.

It should be noted that the arrows indicating relationships between the conceptual elements differ from those employed in the figure in Section III. This is because Figure 5 is addressing long-run relationships with regard to production.

V. Concluding Remarks

We recognize the considerable ambiguity in the presentation contained in this paper. This is because of the encompassing way we have formulated our conceptual elements. Thus, for example, Boundary Conditions (C) contains many aspects, including not only various physical factors, but also political, legal, social, and economic factors.

Further, our typifications of several economic schools has been in terms of those generalities which we see as relevant to the purpose of our paper, viz. the role of time in economic analysis. We recognize that such typifications may invite severe criticism from the adherents of the various schools.

Finally, we have not differentiated in an operational way between short-, medium- and long-run considerations. Similarly, our three types of Time Irreversibility are broadly drawn in such a manner that they can be applied in many ways.

These areas of ambiguity clearly demand a great deal of further work, both for further clarification of the issues involved, and for making substantive progress in addressing these issues. To these ends we propose to undertake the following programme of research.

a) The role and importance of ignorance, uncertainty and the emergence of novelty need to be explicitly recognized in economic analysis, particularly in long-run studies, such as those concerning resource use and the environment.

b) Recognition must be given to the role of the natural environment in providing both limits to economic activity, and simultaneously a stimulus to invention and economic development. We feel that this requires the economics profession to become much more open to the work of natural scientists; interdisciplinary work is vital here (Faber and Proops 1985).

c) So far, there have been two major types of response to uncertainty and the emergence of novelty by the economics profession. The first has been to neglect these issues, and concentrate on rigorous modelling involving only certainty or risk (the Neoclassical school). The second has been to embrace them so wholeheartedly that modelling and formal representation are seen as impossible (Austrian Subjectivism). As an alternative, we urge that a step-by-step approach to these issues be adopted, as is being pursued by some Evolutionary economists (Nelson and Winter 1982; Witt and Perske 1982; Cross 1983; Witt 1987), with formal modelling being used in particular problem areas. However we also urge that the modelling concentrate, as a first priority, on providing insights; insights should not be sacrificed for the sake of mathematical formalization.

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