Irreversibility

Faber, M., Frick, M., Zahrnt, D. (2019) MINE Website, Irreversibility, accessed on 20 January 2019, www.nature-economy.com

Abstract

During the 19th century, new insights into the concept of irreversibility were developed with the founding of thermodynamics. It turned out, that an understanding of time irreversibility requires a thermodynamic underpinning. In the second half of the 20th century, the physical chemist Ilya Prigogine discovered ground-breaking insights regarding irreversibility in self-organising systems, such as biological plants. The economist Georgescu-Roegen introduced the physical concept of irreversibility into Ecological Economics. Mainstream Economics has a flawed view of temporal irreversibility in production theory since it neglects important thermodynamic considerations, for instance it generally assumes that all goods can be substituted by others.

Ecological Economics argues that a thermodynamic understanding of irreversibility is necessary to adequately analyse the interplay between nature and economy. For ease of understanding, let us assume that time is reversible. Accordingly, time has the same status as a spatial variable; hence time can move in two directions, into the past and into the future. Thus, its direction is not uniquely defined, and past and future can be treated symmetrically. However, as soon as we experience real time, we note that we are only able to move in one direction, namely from the present to the future, for we cannot return to the past. So, a good definition of irreversibility is: A process is irreversible if it is not possible to reverse it.

Thermodynamic irreversibility restricts economic actions in time (Georgescu-Roegen 1971). Only those actions are possible that are not restricted by the two laws of thermodynamics. Hence, thermodynamic irreversibility is a constraint for economic action.

A practical example of irreversibility is the burning of a piece of coal. Once burned, you can never turn it back into coal.

Related concepts: THERMODYNAMICS; EVOLUTION; BASICS OF TIME; BASICS OF LIFE

1. History

In physics there has been a tremendous change over the past two hundred years in the way scientists view time This is also true of time irreversibility.

"Before 1850 the paradigm governing physics was Newtonian Mechanics. The law of gravitation and Newton's three laws of motion allowed the description of the motion of bodies and their interactions in the form of equations which are, in the absence of energy dissipation, symmetrical with respect to replacing the time variable t by –t. Such motion is said to be reversible in time. That means, if some motion of a body is in accordance with Newton's laws, then the same motion running backward in time is also perfectly consistent with Newton's laws and could not be ruled out on physical grounds. For instance, the planets rotating around the sun would, if someone suddenly 'switched´ time from running forward to running backward, just rotate the other way around the sun. This is a result which, in the framework of Newtonian Mechanics, does not contradict any physical law. Indeed, in frictionless mechanical systems, time plays the role of a fourth spatial variable (Prigogine 1980, Prigogine and Stengers 1984) in the sense that past and future are essentially equivalent. This interpretation of time which views the future nearly as a continuation of the present, without any occurrence of novelty of evolution, is captured in the idea of 'Laplace's Demon' (Prigogine and Stengers 1984: 75). This idea states that, given the present positions and velocities of all particles in the universe and its boundary conditions, one can infer their past and predict their future with equal facility" (Baumgärtner et al. 1995a: 9-10).

After 1850, fundamentally new insights into the notion of irreversibility were developed in the course the development of thermodynamics [see concept THERMODYNAMICS; in particular the remarks on the findings of the Second Law of Thermodynamics]. In the second half of the 20^{th} century, Ilya Prigogine (1917 – 2003), with his ground-breaking work on dissipative structures, paved the way for the application of the notion of irreversibility in self-organising systems, such as plants in biology or firms in the economy.

It was Georgescu-Roegen (1906 – 1994) who introduced the physical concept of irreversibility to Ecological Economics in his pioneering monograph (1971). "It is our conviction that Mainstream Economics needs conceptual re-orientation with respect to time irreversibility, not unlike that which has occurred in natural science" (Faber and Proops 1998: 84).

2. Theory

First, we give two interpretations of irreversibility (Section 2.1). Then we introduce the concept of reversible time (Section 2.2). These considerations allow us to deal with two Arrows of Time. The first explains why our universe tends toward a ‘thermal death’ (Section 2.3), and the second explains why increasing complexity exists (Section 2.4). We apply these insights to Economics in Section 2.5 where we deal with self-organisation in particular. In Section 2.6, we relate irreversibility to historical time and in Section 2.7 to evolution.

2.1 Irreversible time

When speaking about our understanding of time [BASICS OF TIME], “one has to stress the importance of the ‘irreversibility’ of time. However, when discussing ‘irreversibility’, one needs to be careful as the term may be given two interpretations. Both relate to the state of knowledge about the world.

First interpretation: processes are irreversible because time only runs ‘one way’

This first interpretation is that processes are irreversible because time only runs ‘one way’, from the past to the future. This interpretation may be better termed the ‘asymmetry’ of time [BASICS OF TIME]. The statuses of the past and the future are different, and this difference derives from the fact that the past has already happened and is known to some extent, while the future has yet to happen and therefore is unknown. This we can relate to our ignorance [IGNORANCE] and the possibility of the emergence of novelty [EVOLUTION]. The future is unknown because our knowledge is limited, and novelty may occur. In contrast, our knowledge of the past is albeit incomplete, more reliable, because novelty that was to emerge has already occurred.

Second interpretation: the ‘appearance’ of a process

The second interpretation relates to the ‘appearance’ of a process. Suppose a film were made of a process and then run backwards. Would the process still appear ‘natural’? If it did, we could say that the process is ‘time reversible’. If not, we could say the process is ‘time irreversible’. Here, knowledge of the world tells us that certain processes have certain appearances over time. Certain things happen first, and then other things happen later. It is, of course, the existence of such irreversible processes that indicates the 'direction' or 'arrow' of time. This point is taken up in more detail in Sections 2.3 and 2.4 below" (Faber and Proops 1998: 64).

2.2 Reversible time

As mentioned above, reversible time is like a spatial variable. Its direction is not uniquely defined so that the future and the past are treated symmetrical.

Newtonian Mechanics and Mainstream Economics

"It has been suggested (Mirowski 1984) that the explicit acceptance of the Newtonian Mechanics as a guide for modelling economic systems by the neoclassical economists William Stanley Jevons (1835 – 1885) and Léon Walras (1834 – 1910) has caused general equilibrium analysis, the theoretical core of Mainstream Economics, also to exhibit time reversibility (Proops 1985). In fact, general equilibrium analysis treats static allocation problems in formally the very same way as intertemporal allocation problems (see for details Faber and Proops 1998: 74-78).

'After General equilibrium theorists gave their description of a general equilibrium with dated goods and state-contingent goods, the apparent distinction between static and dynamic disappeared from equilibrium analysis…. The choice could be between apple as and oranges. Or it could be between apples and today and apples tomorrow' (Romer 1994: 11). In this Mainstream Economics' world, time only plays the role of some parameter. Although all quantities carry the time label, there is not truly dynamic evolution [EVOLUTION], in the sense of change and of occurrence of novelty [IGNORANCE]. Rather, the evolution is 'pseudo-dynamic' in that the time label serves to project future state out of a present static equilibrium state. In the most trivial case, this results in steady-state evolution, i.e. all sectors of an economy grow at the same rate, which is hardly ever observed in reality; for this implies that all production factors, such as labour, capital goods, resources etc. grow at the same rate, too. This procedure is perfectly in line with the idea of Laplace's Demon (see above Chapter 1 above).

Concern about dealing with time in Mainstream Economics

There is more and more concern in Economics about how Mainstream Economics deals with time (see e.g. Faber and Proops 1985, 1986, 1989). For instance, Romer gives an illuminating explanation of why 'any analysis that treats a dynamic economy as being formally equivalent to a static economy characterised by plenitude - fullness in the set of goods – cannot … capture the essential aspects of growth and change' (Romer 1994: 20)" (Baumgärtner et al. 1995: 9-10; Faber et al. 2002: 103-104).

2.3 The First Arrow of Time: tendency toward "thermal death" in isolated systems

We turn now to the second interpretation of time irreversibility, *the 'appearance' of a process*, mentioned in the previous section.

"The everyday experience that time matters, in the sense that processes in macroscopic systems are irreversible in time, gave rise in the middle of the 19^{th} century to the formulation of the Second Law of Thermodynamics [THERMODYNAMICS]. Its statement that, in Clausius' terms, the entropy of an isolated system (i.e. a system which is closed concerning energy and matter) always increases or remains constant, but certainly never decreases [THERMODYNAMICS], allows one to define a time direction, the so-called First Arrow of Time (Layzer 1976).

For example, an ice cube placed in a container of hot water will melt to make cooler water. The ice and water, initially distinctly cold and warm respectively, become mixed up. We never observe cool water separating out of its own accord into cold ice and warm water. If the process of melting were documented in a movie, and this movie were shown to somebody once running forward and once running backward, then this person clearly could rule out the latter as unphysical and identify the former as representing the real process. In this sense, the process of melting or mixing up is irreversible in time.

The tendency of our universe toward 'thermal death'

In its phenomenological formulation by Clausius [THERMODYNAMICS], the Second Law of Thermodynamics states that heat flows from hot bodies to cold bodies, thus increasing entropy, and never vice versa. In its statistical interpretation given by Boltzmann [THERMODYNAMICS], this means that systems have a tendency to ever increasing mixed-up-ness or disorder. It has been suggested that the Second Law of Thermodynamics constitutes the physical underpinning of the fact that the world is developing in one direction, from order to disorder.

William Thompson, the later Lord Kelvin (1824-1907), was the first to formulate this idea [THERMODYNAMICS] in 1852. On the cosmological scale, all differences in temperature and concentration of matter in the universe, in the form of planets, stars and galaxies are predicted to level out. Heat flows from hot to cold, thus reducing differences in temperature; and there is mixing of materials which are initially highly concentrated, thus reducing differences in concentration. The final state of this cosmological evolution is the so-called 'thermal death' of our universe. This is a state where the entropy of the universe is maximal, all potentials (i.e.: differences in temperature or concentration of matter) are levelled out, so that energy and matter are evenly distributed throughout the universe" (Baumgärtner et al. 1995: 10-11; Faber et al. 2002: 104-105).

This would imply that the universe would be in a so-called thermodynamic equilibrium. It is a state "where the system's thermodynamic variables (e.g. temperature, pressure, etc.) are constant. Such equilibrium is most easily understood for an isolated system, where no energy or matter can enter or leave. In the popular literature on thermodynamics, one comes across the notion of the thermal death of the universe, mentioned above, when all chemical and thermodynamic potentials are exhausted, leaving a very cool, homogeneous system. This is, however, a contentious notion, as it would require that the universe is an isolated system, for which there is currently no evidence" (Faber and Proops 1998: 24).

2.4 The Second Arrow of Time: self-organisation and increasing complexity in open systems

A pessimistic view of the First Arrow of Time in striking contrast to the history of evolution of life

While we have dealt with isolated systems in the previous section, we turn now to open systems, system from which energy and matter can go in and out. The "pessimistic view of development as based on the Second Law of Thermodynamics and the First Arrow of Time described above is in striking contrast to the observation that cosmological history and the history of the evolution of life on earth exhibit a tendency towards even more structure and greater complexity [THERMODYNAMICS; EVOLUTION; BASICS OF LIFE]. Out of cosmic clouds of hydrogen formed stars which developed into galaxies and later even more complex structures. On Earth, out of some basic molecules formed very simple forms of life, such as algae and bacteria, and later out of these emerged more complex forms of life, such as reptiles and mammals. This tendency of systems to generate self-organisation towards more complex structures has been termed the Second Arrow of Time; it also describes irreversibility since it allows one to distinguish between the past and the present.

But how does this tendency to build up increasingly complex chemical, biological, ecological and social structures go together with the claim of the Second Law, namely that components of a system move towards mixed-up-ness? There seems to be a contradiction.

Explaining biological life

Nineteenth century science could not solve this puzzle. The process of biological evolution [EVOLUTION] was regarded as being outside the bounds of explanation by thermodynamics. Only in the 1940s did the physicist Erwin Schrödinger (1887 – 1961) relate the Entropy Law to the phenomenon of life in a pioneering way. He pointed out that whereas the Second Law describes isolated systems, all living systems in nature have to be described as open systems which exchange energy and matter with their surrounding environment. Open systems that are not in thermodynamic equilibrium can maintain their state in the long-run only by importing low entropy from their environment and exporting high entropy: ‘Life feeds on low entropy’ (Schrödinger 1944: 75). The crucial point is that entropy in an open system can be decreased by the exchange of energy and matter with its environment. (Baumgärtner et al. 1995: 13-114; Faber et. al. 2002: 107)

Prigogine ’s pioneering contribution: self-organisation

It was Prigogine and his co-workers in Brussels (Prigogine 1962, 1967; Glansdorf and Prigogine 1971; Nicolis and Prigogine 1977) who studied the behaviour of open systems that are not in thermodynamic equilibrium. They found that open systems not in thermodynamic equilibrium, but close to it, cannot develop a complex order. Such an evolutionary development towards higher order can only occur in open systems far from equilibrium. A sufficient condition is that the through-flux of energy and matter through the system is associated with a sufficiently high flow into the system of negative entropy (i.e. of high order, THERMODYNAMICS] per unit time. Under these conditions the open system may spontaneously exhibit further structuring. This phenomenon of self-organisation through dissipation depends also on the material involved and the boundary condition of the system, such as its geometry. Not all open systems have the potential to develop dissipative structures, and those which have the potential, due to suitable boundary conditions, depend on a sufficient influx of negative entropy (high order) in order to exhibit self-organised evolution towards more structure and higher order.

An illustration

A classic example of dissipative structure far from equilibrium is the so-called Bénard convection cells (Prigogine and Stengers 1984). When the temperature gradient is applied to a liquid, initially heat is transported through the liquid solely by conduction, i.e. through interaction solely at the molecular level. As the temperature gradient is increased, and thus more energy (i.e. more negative entropy) flows through the system, at one critical threshold value of the temperature gradient the liquid will become a dissipative structure, spontaneously generating a completely new, ordered mode of behaviour. Macroscopic hexagon convection cells will form which allow a much more efficient transport of heat through the system than single conduction. The new stage of the liquid is characterised by higher order, but also by higher rate of dissipation of energy, and thus is even further away from thermodynamic equilibrium. It is the more efficient dissipation of energy which enables the system to import a higher amount of negative entropy (higher order) from the environment.

The process of self-organisation

In general, dissipation of energy in open systems, associated with a sufficiently high influx of negative entropy, can lead, through self-organisation, to the formation of spatial or temporal structures. It is characteristic that if one of the parameters describing how far the system is away from equilibrium (such as the temperature gradient in the example of the Bénard convection cells mentioned above) reaches a critical value, the old stationary state becomes unstable. New stable stationary states appear in the system and the system exhibits a discontinuous transition to a new pattern of spatial or temporal order. This new stationary state again becomes unstable when the parameter further increases and reaches another critical threshold value" (Baumgärtner et al. 1995: 15-16; Faber et al. 2002: 108-109).

2.5 Self-organisation in economics

"It has been suggested by Mirowski (1984) and (Proops 1985) that the explicit acceptance by the two founders of (Neoclassical) Mainstream Economics Stanley Jevons (1835 – 1882) and Walras (1834-1910) of Newtonian Mechanics as a guide for modelling economic systems has caused its main paradigm, general equilibrium analysis, to exhibit time reversibility. In fact, general equilibrium analysis treats static allocation problems in formally the very same way as intertemporal allocation problems" (Baumgärtner et al. 1995: 10;

Faber et al. 2002: 103). This implies that no novelty occurs. However, "what has been termed the Second Arrow of Time is an obvious phenomenon in the economy, namely the build-up of capital goods, organisational structure or institutions, and technological progress towards higher complexity. Attempts to explain and model such a tendency go back at least to Malthus (1766 – 1834), Marx (1818 – 1883), Menger (1840 – 1924) and Schumpeter (1883 – 1950) [EVOLUTION]. But with the dominance of Mainstream Economics, which stresses the notion of equilibrium and generally does not give temporal aspects the attention they deserve [BASICS OF TIME], this strand only played a minor role in Mainstream Economics. Only at the end of the previous century did interest return among some researchers of Mainstream Economics [EVOLUTION; HISTORY OF THOUGHT]. In contrast, ecological economists put in their analysis the focus on the dynamic interaction between nature and economy [THERMODYNAMICS; EVOLUTION; BASICS OF LIFE; SUSTAINABILITY & JUSTICE; TELEOLOGICAL CONCEPT OF NATURE].

The physical concept of open systems far from equilibrium constitutes a fruitful heuristic also for describing economic and social systems: 'It is suggested that an economy is, when viewed from a physical perspective, the 'same sort of thing' as an organism, a flame, or a convection cell' (Proops 1983: 354). Many authors applied this concept to economics (e.g. Proops 1983, 1985; Allen 1988; Dycke 1988). They explicitly use the thermodynamic concept of self-organising structures as an analogy for describing economic systems. 'Other recent attempts not directly inspired by thermodynamics, but also concerned with describing evolutionary and self-organisational aspects in technological and economic change, include the field of Evolutionary Economics (Nelson and Winter 1982), a relatively new branch of Mainstream Economics, and the newly emerging 'science of complexity' (Anderson, Arrow, and Pines 1988; Waldrop 1992).

Arthur's approach to exploring the role of mass production

Arthur (1989) has presented a dynamic model which explores the role of returns to scale, i.e. the advantages of mass production, on market shares. He finds that under increasing return on scales small chance events early in the history of an industry or technology can become magnified in a self-organised way, increasing returns acting as positive feedback, so as to determine the eventual outcome. As in open systems far from thermodynamic equilibrium, essential features of the model are sensitive to dependence on small historical events, path dependence and unpredictable outcomes.

Arthur's results even suggest that the dominant technique may be less efficient in the long-run than one of the techniques abandoned in its favour. In terms of road transport for example, he argues that the internal combustion engine came to dominate the steam engine through a series of historical accidents, even though the steam engine had a greater potential economic efficiency.

Evolution of economic systems inspired by the Second Arrow of Time

All of the attempts above mentioned, be they inspired by thermodynamics or not, have in common that they are concerned with describing the evolution of economic systems as the build-up of higher organisational structure [EVOLUTION] and involve the Second Arrow of Time.

Thermodynamics and time irreversibility: banishing the contradiction between degradation and increasing complexity

As we have seen, modern thermodynamics offers a wide conceptual framework to deal with irreversibility. Crucial to the framework is the notion of entropy, first through the formulation of the Second Law of (equilibrium) Thermodynamics [THERMODYNAMICS], and more recently through the developments in the study of *systems far from equilibrium* (Prigogine and his collaborators). The two tendencies, towards degradation and towards greater organisation over time, reflect two aspects of the same phenomenon: The First Arrow shows time irreversibility for systems that are isolated and in thermodynamic equilibrium, while the Second Arrow of Time is operational for systems which are open and far from equilibrium. By making this distinction, we banish the apparent contradiction of the tendency of some systems to move towards ever increasing disorder and the tendency of some other systems towards ever increasing and more complex structures.

Thermodynamics: offering a unifying approach for Ecological Economics

As noted above, whereas Mainstream Economics describes only time-reversible processes, we feel that thermodynamics offers a broad, unifying conceptual approach also to time irreversibility in Ecological Economics. For instance, 'we note that the physical world acts as a constraint upon economic activity, while technical progress [EVOLUTION] is the mechanism by which such physical constraints are eased or transformed… In particular, the intertemporal physical constraints imposed by considerations of resource depletion and environmental degradation are manifestations of the First Arrow of Time while technical progress reflects the generation of novelty [EVOLUTION; IGNORANCE] and therefore invokes time irreversibility.' (Faber and Proops 1998: 94).

Conclusions

Before proceeding, we summarise our insights form the discussion so far.

The thermodynamic approach centred around the notion of entropy [THERMODYNAMICS] offers a unifying conceptual framework to integrate the description of the human economy and its biophysical surrounding. Such an approach stresses some features of economic processes which in Mainstream Economics are not given the prominence they deserve:

1. the transformation of energy and material is subject to the laws or nature. The thermodynamic approach is a way for economics to get in touch with its biophysical foundations [THERMODYNAMICS; EVOLUTION; BASICS OF LIFE; SUSTAINABILITY & JUSTICE; TELEOLOGICAL CONCEPT OF NATURE].

2. In every process there exists a time irreversibility expressed in the two tendencies of the First and Second Arrows of Time. The entropy concept makes one aware of the irreversible nature of environmental and resource processes. On the other hand, creative potential for technical progress and biological evolution is seen to exist [EVOLUTION]" (Baumgärtner et al. 1995: 17-19; Faber et al. 2002: 111-112).

2.6 Historical time and irreversibility

Historical time

We now turn to the second interpretation of time irreversibility. To deal with this interpretation we have to introduce the notion of 'historical time'. This concept allows us to consider the process of learning in real time concerning events which are unknown in the present [BASICS OF TIME; IGNORANCE].

We noted in Section 2.1 above that the second interpretation of time irreversibility is that processes are irreversible because time runs only 'one way', from the past to the future. This interpretation may be better termed the 'asymmetry' of time. Historical time "requires the explicit recognition that the statuses of the past and the future are different, and this difference derives from the fact that the past has already happened and is known to some extent, while the future has yet to happen and is therefore unknown.

"Common experience tells us that the past is unambiguous (though not necessarily known in every detail), while the future is ambiguous in many respects. We usually recognize this in economics by referring to 'risk' and 'uncertainty' as being associated with future states of the world (Knight 1921)" (Faber and Proops 1998: 70). This passage of real time or historical time is essential for learning processes.

In addition, we need to consider a third ambiguity which is of great importance for Ecological Economics; this is the concept of ignorance. However, we shall deal with the latter not here, but extensively in the concept [IGNORANCE] (see for all three notions Faber et al. 2002: Chapter 11).

Risk, uncertainty, and ignorance

Risk means that all future events can be associated with probabilities. This is different in the case of uncertainty where these probabilities are not known; thus, irreversibility is encountered in a starker form. The case is much worse if 'ignorance' exists, where it is not known whether or what will eventually happen. We shall deal with these cases at length in the concept [IGNORANCE].

Relationship between historical time and irreversibility

Time irreversibility may occur in different forms in historical time depending on whether risks or uncertainty ignorance exist. Both cases present two different types of irreversibility, each of which is important for economic analysis.

Risk – irreversible time 1

"The future and the past are treated asymmetrically because of asymmetric information structures, i.e. past events may be known and therefore certain. Future events are not known for certain but can be associated with known objective or subjective probability distributions based on knowledge of the past. In Mainstream Economics this kind of uncertainty is called 'risk'" (Faber and Proops 1998: 71). To illustrate it, consider the weather. Let it be known that in a certain area and time span t to t* the probability of raining is forty percent. After time t* we know whether it rained or not; this fact is irreversible.

Uncertainty – irreversibility time 2

The future may contain novelty in the following sense; although the future event may be known, it cannot be associated with a probability distribution based on knowledge of the past. In Mainstream Economics this kind of uncertainty is called 'uncertainty'." (Faber and Proops 1998: 71f) An illustration is the disaster at the Fukushima Nuclear Power Plant on 11 March 2011. The probability of this event was not known.

Ignorance –irreversibility time 3

The future may contain novelty that is definitely unknowable, i.e. some future events are not known, therefore there is no knowledge about their occurrence. An example is the discovery and toxic consequences after dioxin was emitted at the chemical enterprise Givaudan, a subsidiary company of Roche in Seveso, 20 km north of Milan on 10 July 1976. Before this incident, dioxin and its dangerous repercussions were completely unknown.

We note that these three types of irreversibility are due to natural circumstances. Besides these, humankind knows a fourth kind of irreversibility. This occurs in general if one has a goal (Greek: telos) [BASICS OF LIFE; TELEOLOGICAL CONCEPT OF NATURE] to be reached over time. The related endeavours to achieve that telos are connected with this fourth kind of irreversibility.

Teleological sequence – irreversibility time 4

"Particular goals often require economic developments of particular temporal sequences of decisions and actions. … A teleological sequence can be understood as a social kind of irreversibility. We can distinguish three characteristics of this type of irreversibility:

(a) The time order of the stages of teleological sequence is fixed and hence invariable.

(b) From (a) it follows that each teleological sequence is fixed and hence invariable.

(c) Each teleological sequence is characterised by a goal, its '*telos*'" (Faber and Proops 1998: 72).

An illustration is an enterprise aiming to establish a new branch in another country. Let the telos be to construct a new factory (c). The time order of building the factory, digging the basement, building the walls and constructing the roof, have a definite temporal order (a) and (b). After having built the appropriate factory with its process-specific capital stock, a change in the demand conditions may mean the plant can only yield large losses. Hence, the decision to accomplish this goal turns out to be a grave failure since the investment is, to a large extent or even completely irreversibly, lost. To summarise, a process which is directed towards a specific end is always endangered by a social kind of irreversibility, irrespective of the three other physical irreversibilities 1, 2 and 3 mentioned above.

2.7 Evolution and time irreversibility

In the concept EVOLUTION "we developed notions of phenotypic and genotypic evolution. The former we defined to be the evolution of the realisation of a system's potentialities. The latter is the evolution of the system's potentialities themselves. We noted that phenotypic evolution is, in principle, predictable. On the other hand, genotypic evolution allows for the emergence of novelty, so it is in principle unpredictable [IGNORANCE].

We now wish to relate these two concepts of evolution to the three types of time irreversibility we have developed above. We proceed by considering each type of time irreversibility in turn.

Time irreversibility 1 (risk) is exhibited by processes which have asymmetric information available regarding their past and future behaviour. However, here we are supposing that all possible future states can be enumerated, and probabilities associated with each possible outcome. Thus, processes exhibiting this type of time irreversibility are, at least stochastically, predictable.

Time irreversibility 2 (uncertainty) is more difficult to deal with in two ways. First, even if we can specify all possible future states of the world, there are at least some outcomes with which we cannot associate probabilities.

Time irreversibility 3 ignorance) is the most difficult to deal with, for we may not be able to specify all possible future states of the world. That is, our ignorance may relate not only to probabilities of events, but even to the nature of the events themselves. Clearly a process which exhibits this type of uncertainty about its future is unpredictable.

Time irreversibility 4 (teleological sequence) is, in some ways, the most difficult to classify. The reason for this is that this type of time irreversibility relies upon the notion of an end or *telos* [TELEOLOGICAL CONCEPT OF NATURE]. This *telos* must lie in the mind of an individual or be agreed by a group of individuals. If the *telos* is known, then the process is largely predictable for a given technology. For example, to build a house using current technology, one first digs the foundation, pours concrete, constructs the walls, finishes the roof, etc. However, it may be that the nature of the *telos* is not known. As Austrian Subjectivists stress, all human agents have free will and may decide on goals which are novel and therefore unpredictable (Kirzner 1982; Pellengahr 1986a, 1986b; Faber and Proops 1998: 79-80). Thus, we conclude that the process exhibiting time irreversibility 3 is predictable if the *telos* is known but is unpredictable if the *telos* is unknown.

This relationship of predictability/unpredictability with the three concepts of time irreversibility is shown below:

Risk is predictable, Uncertainty is unpredictable. The teleological sequence with a known telos is predictable, while the teleological sequence with an unknown sequence is unpredictable.

We see that risk and teleological sequence, with a known *telos*, are predictable and therefore should be part of phenotypic evolution. We see this is so as, in both cases, the process involves only the realisation of a system. Its potentialities are unchanged.

Concerning uncertainty, ignorance and teleological sequence with an unknown *telos*, novelty emerges over time, so the potentialities of the system are evolving. The emergence of these knew potentialities must therefore correspond to genotypic evolution." (Faber and Proops 1998: 80-82).

Irreversibility and thermodynamics

We can also relate our four types of irreversibility to the thermodynamic considerations given above, for "both the First and Second Arrow of Time can be related to the four types of time irreversibility. The First Arrow represents the tendency of isolated natural systems to go from a present known state to a future state which is not known with certainty, but about which certain general statements can be made, particularly with respect to increasing entropy [THERMODYNAMICS]. In this respect the First Arrow reflects time irreversibility 1 (risk). However, the First Arrow also has a teleological aspect in that higher levels of system entropy can only be attained by first passing through lower levels of entropy. In this sense the First Arrow also reflects properties of time irreversibility 4 (teleological sequence); viz. (a) time order and (b) direction. Moreover, we wish to emphasise that the First Arrow clearly reflects properties of the phenotypic evolution of systems [EVOLUTION].

The Second Arrow of Time illustrates the tendency of certain open natural systems to exhibit the emergence of structure and behaviour which is novel in a chaotic sense. It can therefore be said to reflect time irreversibility 2 (uncertainty) and irreversibility 3 (ignorance). The Second Arrow also has properties (a) and (b) of teleological sequence, in that complex systems emerge from simpler components.

3. Practice

We shall illustrate reversible processes in Section 6.1 and two kinds of irreversible processes in Section 6.2.

3.1 Reversible processes

Let us consider now the first two examples of reversible processes.

“1. The orbiting of a planet around the sun.

The film, if run backwards, would appear quite natural. The motion of the planet is regular and repetitive, and it is not particularly tending towards any end state.

2. The bouncing of a ball without friction.

As for the orbiting planet, the motion is regular and repetitive, with no particular end. This is also a time reversible process, when run backwards” (Faber and Proops 1998: 65).

3.2 Irreversible processes

In Section 2.1 above, we noted that when discussing ‘irreversibility’ one needs to be careful as this term may be given two interpretations. Both relate to our state of knowledge about the world.

First interpretation of time irreversibility: the ‘appearance’ of a process

“3. The burning of a lump of coal.

The film of this process run backwards would look distinctly odd. We simply would not see diffuse energy combining with carbon dioxide and water vapour to create coal and oxygen. This process is clearly irreversible.

4. The growth of an oak tree.

This is also a process that can only be run one way on film and still look sensible. A mature oak tree gradually shrinking until it forms an acorn has never been observed. This is also time irreversible” (Faber and Proops 1998: 65).

From our knowledge about the world, we are able to conclude the irreversibility of the two processes.

Second interpretation of time irreversibility: processes are irreversible because time only runs ‘one way’.

The following example is different as it concerns what we called in Section 2.6 teleological sequence-irreversibility 4.

5. Teleological sequence: the production of a consumption good.

“The production of goods needs an input of effort. Thus, to manufacture a good generally requires the prior construction of capital equipment. Therefore, the temporal ordering of the process of producing a consumption good would be: produce the appropriate capital equipment and then construct the consumption good. The reverse ordering would be neither possible nor compatible with the aim of producing the consumption good.

In the light of the discussion above about time irreversibility, what are the implications for considerations of time irreversibility in general and for Ecological Economics in the long term in particular?” (Faber and Proops 1998: 65). A detailed answer to this question can be found in Part III of Faber and Proops (1998: Parts III to VI).

3.3 Conclusions

We have learned that irreversibility is an essential concept to characterise time in general and temporal processes in particular. We noted that Mainstream Economics puts its focus on reversible time approaches. “In particular, we see the use of intertemporal equilibrium and many growth models as all taking the reversible time approach. In these models the time variable does not have a uniquely defined direction. Thus Leijonhufvud (1984: 30) wrote: ‘By itself, the dating of goods only adds dimensions to the commodity space considered in ‘timeless statics. ... dating brings in future time, but it does not necessarily help in bringing in the passage of time.’” (Faber and Proops 1998: 74).

This tendency of Mainstream Economics “has led to a divorce between economic theorising and conceptual framework on the one hand and change in reality. In particular, the irreversibility of time has fallen victim to this trend to closure.

The problem of how to explicitly recognise time irreversibility is not unique in Mainstream Economics. Natural science has also been forced to confront this problem and has been singularly successful in this, first through the formulation of the entropy concept [THERMODYNAMICS] for near (thermodynamic) equilibrium systems, and more recently through developments in the study of the far-from-(thermodynamic)-equilibrium system.

This recent work has required two types of advancement: The first concerns a change in the conceptual framework with respect to time, with the overthrow of the Newtonian mechanical paradigm and the recognition of two tendencies, towards degradation (First

Arrow of Time), and towards greater organisation over time, reflecting two aspects of the same phenomenon.

The second and related development has been the formulation of mathematical techniques to examine nonlinear dynamic systems. We feel that Mainstream Economics now needs to follow the lead set by natural science" (Faber and Proops 1998: 92-93) as Ecological Economics has done.

"Finally, we note that the physical world, of which time irreversibility is a very important aspect, acts as a constraint upon economic activity, while technical progress is the mechanism by which such physical constraints are eased or transformed [EVOLUTION]. Mainstream Economics has neglected intertemporal constraints imposed by considerations of resource depletion and environmental degradation, manifestations of the First Arrow of Time (i.e. irreversibilities 1 and 3, as defined in Section 2.6), while technical progress reflects the generation of novelty and therefore invokes time irreversibility 2" (Faber and Proops 1998: 94).

4. Literature

The content of MINE originates from scientific work published in books and peer-reviewed journals. Quotes are indicated by a special typographic style.

The project team would like to thank the publishers **Edward Elgar**, **Elsevier**, **Routledge**, **Springer** and **Taylor & Francis** for granting a reproduction permission.

Furthermore, we want to express our gratitude to Bernd Klauer, Reiner Manstetten, Thomas Petersen and Johannes Schiller for supporting the MINE Project and granting the permission to use parts of the content of their book "Sustainability and the Art of Long-Term Thinking."

We are indebted to Prof. Joachim Funke, Ombudsman for Good Scientific Practice at Heidelberg University and the legal department at Heidelberg University, for their advice and support.

The main source of this concept is the following publication:

Faber, M. and J.L.R. Proops in cooperation with Reiner Manstetten (1998) Evolution, Time, Production and the Environment (3rd edition) Springer Verlag, Heidelberg. Reprinted by permission from Springer Nature Customer Service Centre GmbH **(Licence Number: 501444457; 4474111357591; 4474111297415; 4474111237236; 447411141771).**

4.1 Recommended literature

Key literature

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4.2 Irreversible time

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