The Evolutionary Approach to Entropy: Reconciling Georgescu-Roegen's Natural Philosophy with the Maximum Entropy Framework

by

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The paper explores the relevance of recent developments in the Maximum Entropy hypothesis for reinstating Georgescu-Roegen's natural philosophy, with special emphasis on the concepts of evolution and time. The key point is the naturalization of the notion of 'subjectivity' in both the Georgescu-Roegen framework and Jaynes's subjectivistic interpretation of thermodynamics and statistical mechanics. I introduce the concept of 'observer relativity' with reference to the evolution of 'physical inference devices'. Then, the MaxEnt formalism can be understood as a principle underlying natural selection. Further, given natural selection, maximum entropy production (MEP) results from the confluence of maximum power (Lotka) and the maximization of information capacity, driven by energy dispersal. In these processes, hierarchical structures of gradients of energy dissipation reflect alternative positions of system boundaries, and hence different perspectives of observer-relativity. Thus, I can distinguish between observer relative Entropy$_{OR}$ and observer independent Entropy$_{OI}$. This allows to reconstruct conceptually the two notions of time proposed by Georgescu-Roegen, with subjectivistic time seen as time relative to the evolutionary process involving incommensurable qualitative change. I claim that this philosophical view offers a powerful conceptual framework for recent empirical research into the energetics of economic growth.

Keywords: Georgescu-Roegen, Jaynes, Lotka, maximum entropy, observer relativity, time, natural selection, physical concepts of information

JEL classification: B52, Q57

FORTHCOMING IN ECOLOGICAL ECONOMICS

1. Revisiting the ‘entropy law’ from the perspective of Maximum Entropy

Since Nicholas Georgescu-Roegen introduced the notion of entropy into economics, the discussion has revealed a number of misconceptions and even mistakes in his seminal approach, which, however, did not result into a wholesale rejection of the thermodynamics agenda in economics. The constructive side of the response is mainly reflected in the search für empirical regularities in long-run trends in energy consumption, based on the notion of exergy (see e.g. Ayres and Warr 2003, 2005; Warr et al. 2008), which in turn can build on standard approaches to thermodynamics in engineering, since the intermediating factor is evolving technology. Exergy is a concept that is embedded into thermodynamics, but which differs from the more fundamental concepts of the general laws of thermodynamics in being contextualized, i.e. empirically determined with relation to specific physical environments, and thus being more directly amenable to economic analysis. Compared with this approach, the notion of entropy appears to be overly abstract and irrelevant for economic analysis, leaving by far too many degrees of freedom in interpretation (for a comprehensive survey, see Bünstorf 2004). In contrast, the negative response to Georgescu-Roegen mainly concentrates on some flaws in his arguments, which have also been pointed out by physicists (e.g. Jaynes 1982). These are, in particular, his strong opinions against the statistical mechanics foundation of entropy and his attempt at amending thermodynamics by a new ‘law’ referring to material flows. Those critics reinforce the argument about the irrelevance of entropy for economics in emphasizing its insufficiency in dealing with the evolution of resource constraints in the economy, thus questioning the direct connection between thermodynamics and ecological and environmental economics which Georgescu-Roegen had established (e.g. Khalil 1990, Gillett 2006).

In this paper, I explore this contested ground again, armed with a number of new conceptual approaches to entropy that have emerged recently in the context of the Maximum Entropy school in physics and the geosciences, in particular. This approach differs from most conceptualizations of entropy in the economics literature as the Maximum Entropy production hypothesis is applied on steady states of open non-equilibrium systems, so it is more general than the standard equilibrium thermodynamics and the dissipative structures approach in non-equilibrium thermodynamics. As many problems with the original Georgescu-Roegen approach result from the mismatch between the equilibrium concepts of standard thermodynamics and the fact that the human economy is an open equilibrium system, the Maximum Entropy approach might offer a fresh perspective. I emphasize right from the beginning that I am not concerned with the Georgescu-Roegen argument about thermodynamics and resource constraints which I consider to be flawed for the case of an open Earth system anyway, and given growth of technological knowledge with qualitative novelty. My concern is the question whether thermodynamics generates certain most universal propositions about the direction of change in the economy and its underlying mechanisms, which thermodynamics would relate with the general phenomenon of the dissipation of energy in evolving physical structures and the corresponding production of entropy (thus concurring with strands of thought such as Lozada 2006).

Georgescu-Roegen's way of thinking was driven by some fundamental philosophical propositions, which become highly relevant here. Therefore, I also adopt an analytical-philosophical stance, which translates into the attempt at drawing a new conceptual map for placing entropy in the context of economics. Here, two notions loom large. One is the notion of evolution. Georgescu-Roegen's attack against the statistical mechanics approach to entropy is based on his fundamental distinction between 'arithmomorphic' and 'dialectical' theories, hence emphasizing the principled role of qualitative novelty in evolution. His other notion is the distinction between two conceptualizations of time, the time of mechanical physical clocks and time as a flow through human consciousness. He argues (1971: 130ff.) that the time's arrow cannot be established by the former, but only by the latter, which implies that its direction cannot be deduced from the laws of thermodynamics directly. Thus, evolution, entropy and a subjectivistic epistemology conflue in shaping Georgescu-Roegen's idiosyncratic view on the role of the 'entropy law' in economics.

I will present a fresh perspective on this fundamental philosophical stance by introducing an equally philosophically grounded interpretation of the Maximum Entropy school in physics, which is so far neglected in the economics debate, to my best knowledge (compare its omission in Ruth 2005; Ayres 1994: 36 has only a cursory reference to this, though affirmatively; similarly, e.g. Kåberger and Månsson 2001). This is significant both for purely theoretical reasons and for empirical research. The former stays at the center of my attention, so suffice to emphasize the second now: One important field of applying the Maximum Entropy approach is the geosciences or Earth system studies, and obviously the human economy is a part of these larger systems. So, empirical support in favour of the Maximum Entropy approach with regard to the Earth system directly raises the question how far the economic subsystem follows similar principles (Kleidon 2010b; for a critical view on entropic approaches to the Earth system-economy interaction see e.g. Smil 2008: 341ff.).

The Maximum Entropy school goes back to the seminal work by Jaynes (1957a,b) on proposing a radical shift in interpreting the concept of entropy. In this view, entropy turns out to be the central conceptual category in drawing inferences about physical systems about which only limited information is available. This approach, labelled ‘MaxEnt’, is no longer focusing on physical phenomena in the strict sense, but on the methodology of how to draw inferences about them. This shift is rooted in the Gibbs approach to entropy and thus establishes a different path to tackling the Georgescu-Roegen issues, who almost exclusively focused on the Boltzmann line of thinking in his critical endeavours and the classical phenomenological thermodynamics in his own approach. Subsequently, I show that the treatment of the Second Law of Thermodynamics as a ‘rule of inference’ (Jaynes 1998) allows for a reconsideration of Georgescu-Roegen’s views, which, though refuting his criticism of the statistical mechanics approach again (though with a different emphasis), reinstates some of his central arguments on evolution and the economy.

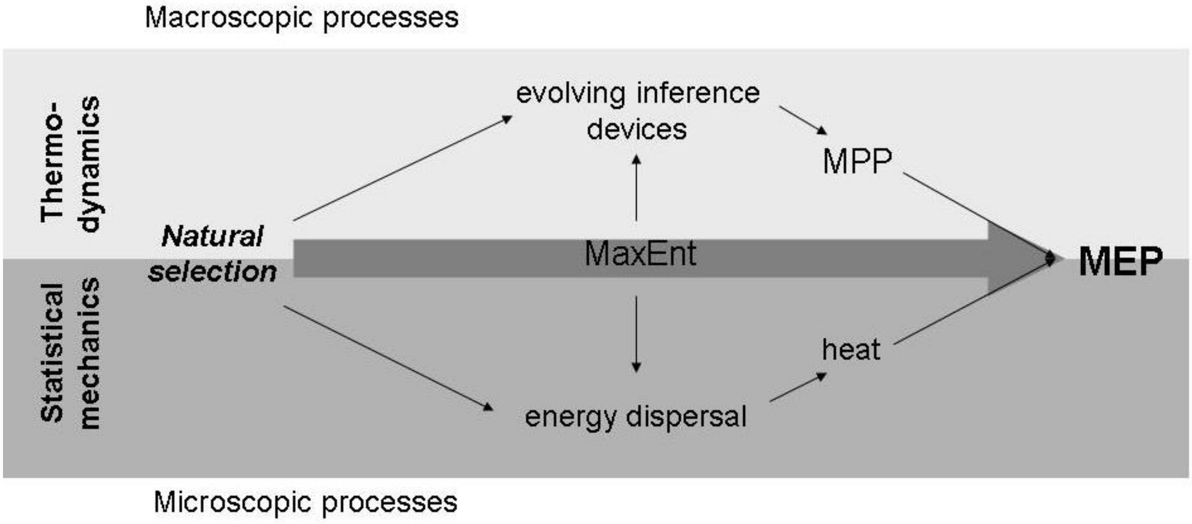
My argument is not without precedent in ecological economics. One central question is how the thermodynamic and the information theoretic meaning of ‘entropy’ can be reconciled, which sit awkwardly in between the disciplines, because a formally homologous concept has two very different material interpretations. In the Maximum Entropy school, this tension can be easily resolved because a more general mathematical formalism is offered in which the information theoretic standard use (i.e. the Shannon approach) is just a special case in the context of the analysis of communication systems (Jaynes 2003: Chapter 22; for the generic mathematics, see Niven 2007). Instead, the Maximum Entropy formalism appears to be a much more general information theoretic framework in dealing with inference processes of any kind, including inferences about standard ensembles of thermodynamics and statistical mechanics as the classical case (but also, for example, inferences about complex social networks, see Newman 2010: 565ff.). As such, this approach is familiar to econometricians (Golan 2002). However, the core insight by Jaynes went far beyond a simple application of entropy as a principle of inference in the narrow sense, because for the physicist, the fact remains essential that the inferential notion of entropy corresponds to experimental facts about entropy. This has also been the starting point for relating the MaxEnt principle of inference with the Maximum Entropy Production (MEP) principle in the geosciences (Paltridge 2009, looking back on his seminal work in the past three decades): How far does the successful application of MaxEnt approaches in predicting complex Earth system dynamics imply that those systems also maximize the production of entropy as a physical magnitude in the sense of classical, hence phenomenological thermodynamics? The significance of this question results from the fact that the MEP principle refers to open non-equilibrium systems (and not only to equilibrium systems, as classical thermodynamics), and would therefore assert a most general hypothesis about their trajectories, namely that they approach a steady state in which the production and export of entropy to their environment is maximal (for a short and concise statement, see Kleidon, Mahli and Cox 2010). So, a complete statement of the Maximum Entropy approach includes both MaxEnt as an inference method and MEP as a physical hypothesis.

The conceptual conjunction between thermodynamic and information theoretic uses of entropy has been presaged in ecological economics by Robert Ayres (1994) in his attempt at reconciling the the two. Ayres had already developed two important insights, starting out from an observation that directly matches with Georgescu-Roegen's original qualms with statistical mechanics: This is that information is an *intensive* (hence, qualitative, or dialectic variable, in Georgescu-Roegen's parlance), whereas entropy in thermodynamics is an *extensive* variable (Ayres 1994: 36). One of Ayres' important insights is that there is a direct physical relation between Shannon information H and thermodynamic magnitudes, because the former can be interpreted as a general measure of distinguishability of a system from its environment (Ayres 1994: 44, $H = B / T_0$, with H the Shannon information, B the available useful work, and T_0 the temperature of the environment). The other is to differentiate between this thermodynamic concept of information (D-information in his terminology) and the evolutionary one, which is survival relevant information (SR-information). The latter refers to a selective context in which a certain information proves to be functional with reference to differential reproduction.

Based on Ayres's contribution, I propose a new philosophical approach to entropy (further developed in Herrmann-Pillath 2010; Herrmann-Pillath and Salthe 2010). The central idea directly follows from recent advances in applying the MaxEnt approach on the theory of evolution (for an overview, see Whitfield 2005, 2007). This triggers a surprising twist in dealing with the Georgescu-Roegen issue: Whereas Georgescu-Roegen confronted statistical mechanics and evolution, the shift towards the Jaynes approach in interpreting the former implies that evolution can be seen as a process maximizing entropy. My extension of this view builds on evolutionary epistemology and endogenizes the position of the observer in the inferential approach to entropy: I argue that, if the MaxEnt formalism is the correct and most parsimonious way to form expectations about the behavior of complex systems, this also applies for the evolution of endogenous observers under natural selection. In this view, every living system is conceived as a 'physical inference device' (Wolpert 2008), and natural selection results into the emergence and universal prevalence of inference devices which follow the MaxEnt formalism. Having achieved this change of perspective, I can relate the MaxEnt approach with another argument on the relation between thermodynamics and evolution, namely Lotka's principle of Maximum Power. Both approaches concur in the view that the standard laws of thermodynamics have to be supplemented by the principle of natural selection, which ultimately guides both information processing in evolution and the corresponding energy flows. Taken together, the original extension of the 'entropy law' by Georgescu-Roegen can be vindicated in a principled way.

Fig. 1: Conceptual map of the argument

There are two sets of theories, phenomenological thermodynamics and statistical mechanics, which relate to the macroscopic and the microscopic level, respectively. The distinction between the levels is relative to an observer with limited information capacity. When dealing with living systems, the theories are supplemented by the principle of natural selection which bridges the two levels. Natural selection drives the emergence and evolution of biological structures as physical inference devices, i.e. evolution generates and accumulates information. Physical inference devices evolve according to the MaxEnt principle, which physically corresponds to the process of energy dissipation on the microscopic level. Macroscopically, evolving inference devices manifest MPP, following Lotka's analysis of natural selection. The processes on the two levels conflue in maximum entropy production. Evolution under natural selection results into MEP.



The conceptual structure of my argument is overviewed in fig. 1. I proceed as follows. In section 2, the main part of the article, I discuss the two versions of the maximum entropy approach, MaxEnt as an inference method, and MEP as a physical theory about open non-equilibrium systems. I offer a conceptual unification in the context of evolutionary theory. In section 3 I discuss how this can be related to Georgescu-Roegen's notion of time. Section 4 shows the relevance of the argument for ecological economics. Section 5 concludes.

2. Evolution and Maximum Entropy Production

2.1. Observer relativity with reference to physical inference devices

The current debate over the Maximum Entropy principle girates around the distinction between the MaxEnt principle and the Maximum Entropy Production (MEP) Principle. The MaxEnt Principle interprets entropy as a lack of information on part of an observer. MaxEnt just states that an observer should assume the most probable distribution of an partly unkown set of events over a state space, given certain constraints. The MEP principle relates with phenomenological thermodynamics and refers to the physics of energy flows, thus introduces the additional assumption that the observed physical system will also realize the most probable state by means of producing and exporting entropy. It is a still contested issue whether the two principles are ultimately the same physical propositions, or, whether MaxEnt necessarily implies MEP; yet, important advances towards a unification have been made by several authors which are sufficiently promising to take this as a point of departure for my philosophical discussion (Martyushev and Seleznev 2006; Dewar 2009; Niven 2009, 2010). Therefore, I discuss the two in turn in the subsequent subsections.

The reference to an observer in the MaxEnt principle has been labelled a 'subjectivistic' view in Jaynes's (1957a,b; 1965) original approach, thus referring to what is fundamentally a Bayesian conceptualization of the underlying probabilities (Jaynes 2003). However, the notion of 'subjectivity' is imprecise against the background of recent developments in analytical philosophy. 'Subjectivity' as a description of internal states of observers has to be distinguished from the 'observer relativity' of the pertinent processes under consideration. 'Subjectivity' relates with internal mental states exclusively, whereas 'observer relativity' holds for all reactions of an observing entity to an external event which are based on an internal information processing capacity (compare Dretske 1981). This move to a more differentiated ontological structure prepares the ground for considering the possible convergence between the two notions of 'subjectivism', the Jaynes one and the Georgescu-Roegen one.

The distinction between observer independent (OI) and observer relative (OR) facts has been made a cornerstone of naturalistic ontology by Searle (Searle 1995, 2004). An observer independent fact is a fact that exists without relation to an act of observation, such as a rock or a tree. An observer relative fact is a fact that exists because there is an observer. In the first place, this includes all what philosophers call qualia, such as pain, but also a vast domain of social and cultural facts, such as money or a fence. Entities can have both properties: The fence exists independent from an observer, but even if it is easy to climb, it becomes an almost insurmountable barrier as a legal fact, which is observer relative.

Searle mainly thinks of human observers, and hence relates OR facts to mental phenomena, as he deals with the analysis of social systems when applying this distinction. However, it is straightforward to extend the notion of observer relativity to any kind of process involving an ‘observation’. All living systems manifest processes of observation, as when a bacterium screens its environment for nutrients (Ben Jacob 1998). Under natural selection, these processes operate according to certain energetic principles, which have been summarized by Elitzur (2005) (in more detail, see Lahav et al. 2001, Ben-Jacob et al. 2006; compare Corning 2005: 361ff.). Living systems form structures which extract environmental information, given energetic constraints, such that under natural selection energetic flow patterns emerge that are more efficient, relative to the fitness landscape of their environment (more efficient use of energy, higher power output, improved structural match etc.). In principle, this view matches with Ayres’s (1994) aforementioned notion of SR-information, which we can therefore also classify as observer-relative. From this follows that in considering living systems, we have to distinguish two modes of analysis: One is to treat them as OI facts (e.g. systems of chemical reactions), the other is to see them both as observers, hence as reference points for OR facts, and as OR facts themeselves, relative to other living systems. So, for example, a prey is an OI fact when analyzed in terms of biochemistry, but an OR fact if analyzed in terms of behavioral ecology.

Thus, we can formulate more abstractly that any process which generates information is an observation, which relates this concept into a special category of causality, namely a function (for an early related view, see Bateson 1979; in more detail, see Herrmann-Pillath 2010). Thus, Searle’s notion of observer relativity boils down to the notion of ‘relativity with reference to evolved functions’. This interpretation follows the approach taken in teleosemantics and other teleological approaches to mental content, which reduce intentionality and meaning to evolved functions (Dretske 1981, 1995; Millikan 1989; MacDonald and Papineau 2006; Neander 2009). Thus, a principled convergence can be achieved between the concept of evolution as a process that generates and accumulates information and the idea that the human observer is a special case of the more general case of systems of evolving functions that drive the emergence and diffusion of information under certain energetic constraints. I call those systems 'physical inference devices'. This view can be related to the more general view of evolutionary epistemology (Popper 1972; for a survey, see Bradie and Harms 2008), which sees human knowledge, firstly, as resulting from evolutionary processes in the mind/brain (compare Edelman 2006), and secondly, as being embedded into the larger evolutionary process, thus reflecting natural selection in the most universal sense. This view provides the foundation for a synthesis between the concepts of evolution, entropy and epistemology.

The upshot of this argument is that the notion of 'subjectivity' has to be substituted by the more general and at the same time more precise notion of 'observer relativity', in which the 'observer' is a certain evolved entity, or, even more general, is a local state in the process of evolution. This substitution of the term 'subjectivity' by an evolutionary notion of observation has far-reaching implications for interpreting the use of the term subjectivity in both the Jaynes and the Georgescu-Roegen approach to entropy. I claim that this 'naturalization' of the concept of observer-relativity clears the ground for a reconciliation of the two approaches to entropy.

2.2. Evolution conditions MaxEnt and manifests Maximum Entropy Production

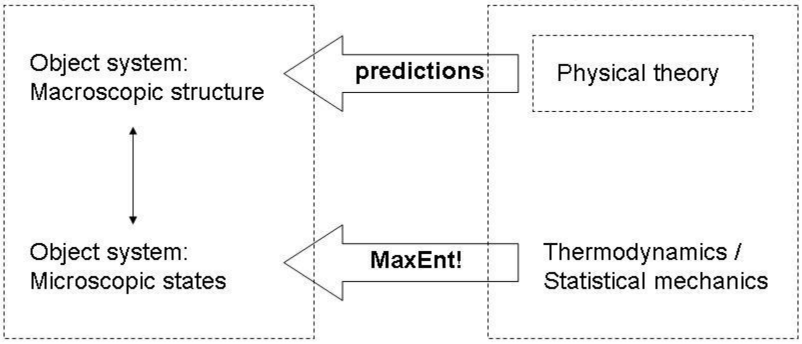
2.2.1. MaxEnt: A principle of selection

Dewar (2009) has argued recently that MaxEnt as inference method plays a principled role in the theory of entropy and in physics generally (see also the original statement by Jaynes 1998). The original Gibbs-Jaynes approach treated entropy as a measure of ignorance on part of the observer of a system. The entropy of a system is the maximum number of microstates compatible with a set of macrostates, given certain constraints on the system. The MaxEnt principle states that in predictions of macrostates, the observer should choose those states in which the related microstates manifest the maximum entropy, i.e. are the most probable ones, given the constraints.

This entropy is not an absolute value, because it depends on the constraints on the macrostates that are considered as being relevant by an observer. As Jaynes (1965) has demonstrated forcefully, entropy – in my notation – is an observer relative magnitude, because it depends on the setting of macrostates and the constraints. In physics, these are experimental settings which depend on the choice of a theory and the pertinent physical variables. Thus, in Jaynes' own example, the entropy of a crystal is different depending on whether one considers temperature, pressure and volume, or when one considers temperature, strain and polarization. Hence, Jaynes concluded that entropy is an ‘anthropomorphic concept’. In Niven’s (2007) parlance, the underlying notion of an ‘ensemble’ is a ‘mental phenomenon’, that is, it is an OR fact. This relates with Ayres’s (1994: 46, 238ff.) view that D-information is relative to a reference state, which is in turn chosen by an observer. Reference states can be simple (such as the Earth atmosphere in chemistry) or very complex, as in the case of living systems (compare Ulanowicz 1997: 24ff.), resulting in increasing degrees of freedom in determining their entropy. Observer relativity is an essential feature of the information theoretic conception of entropy (see also Kåhre 2002: 181ff.) and it emerges in economics contexts (as in ecology in general) in the difficulties in ascertaining relative states of entropy of inputs and outputs, relative to particular production and consumption processes (see e.g. Kåberger and Månsson 2001).

Fig. 2: The MaxEnt principle

A complex system is differentiated into macroscopic states and microscopic states. Future macroscopic states are predicted by choosing the maximum entropy microstates, given the constraints on the system.



In Dewar’s (2009) concise summary, the Jaynes approach can be turned dynamic in the sense of generalizing over the MaxEnt principle as an estimation technique (fig. 2). In this case, the macrostates correspond to conjectures about the kind, number and structure of macrostates with constraints which are necessary to predict the future change of a system. The MaxEnt principle then simply states that those constraints are identified as the causally relevant ones, at which the entropy of the microstates is maximal. If the latter fails to prove, the constraints have to be changed, in terms of reflecting conjectures of the observer about the system under observation. Thus, MaxEnt is not a physical principle on its own, but only a theoretical and methodological concept that allows to identify the physically relevant constraints on a system.

In other words, the physics is only in the constraints, whereas the notion of entropy turns into a non-physical mathematical concept (compare the original Jaynes 1957b: 172).

Thus, it is straightforward to recognize that MaxEnt establishes an observer relative notion of Entropy$_{OR}$, as the choice of macrostates and constraints depends on the interests of the observer, that is, which kind of physical change is in focus. This explains the formal homology with Shannon entropy as a measure of information, in which observer relativity is constitutive, i.e. depending on arbitrary partitions of the state space, which ultimately depend on the interests of the users of a code to convey a message. In other words (see Jaynes 1957a), if the experimental setting is seen as a source of a message that is sent via noisy channels about the underlying physical reality, it seems straightforward that the observer applies an inference method which is formally homologous to Shannon information.

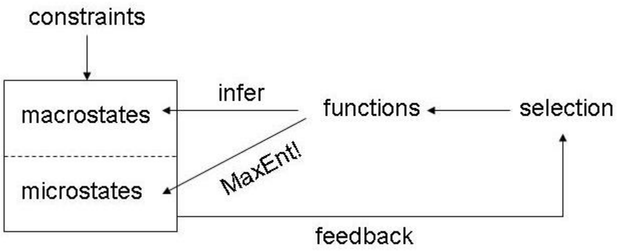
Following section 2.1, we can now formulate a general notion of observer relativity and apply this on MaxEnt. Thus we interpret Dewar's methodological view in the more general context of evolutionary epistemology, i.e. interpret MaxEnt as a feature of evolving information processing systems under natural selection.

This follows from considering the function of the inferences resulting from MaxEnt in the larger embedding systems. In Dewar's account, those functions are the physical theories which are supposed to provide guideposts for successful experimental actions: In this case, we could treat the sciences as evolutionary systems in which (non-natural) selection operates on a population of competing theories and hypotheses (see e.g. Giere 1990). Following evolutionary epistemology and teleosemantics, we can generalize this idea into the naturalistic approach to observation, such that we can say that functions as physical inference devices are the result of natural selection, or, that hypotheses and functions are actually manifestations of the same underlying principles of the generation, selection and diffusion of information. In this view, any biological, technological and other function is seen as a generalized inference device which links a mechanism of prediction with an action that produces causal effects that are relevant in a selective context (for a related approach, see Dennett 1995). That is, the most general purpose inhering a function is the contribution to differential reproduction of the system of which the function is a part.

The central insight is that this means that the determination of macrostates and constraints is an evolutionary phenomenon, in the sense that the functions of the embedding systems evolve. The interpretation of the MaxEnt principle is straightforward in this context (see fig. 3). If Dewar argues that the MaxEnt principle is a way of testing physical theories and adapting them to an unknown and complex reality, we can now say that MaxEnt is property of selection in a complex evolutionary process. In other words, if MaxEnt fails, an observation of an object system fails to cause proper functioning of an observing system because there is a feedback mechanism that reveals that some important constraints on the object system have not been sufficiently included into the function. In contrast, the actualization of MaxEnt means that the observing system has attained a level of functioning in which all other information, beyond the information about the macrostates and constraints of the object system, is irrelevant, and can hence be assigned to the equiprobability measure.

Fig. 3: MaxEnt and selection

MaxEnt is a principle of the selection of function in living systems, because a function is an inference device where correct predictions of macrostates of object systems condition proper functioning. Macrostates under constraints are states of systems which are functionally relevant. The optimal predictive performance is achieved if all other microstates of the object system are irrelevant, hence assigned to the MaxEnt state. All relevant information in the constraints and the macrostates has been extracted by the selection of functions.



Dewar (2009) also presents the essential argument why this works: This is the computational efficiency of MaxEnt. A system that approaches MaxEnt economizes on information because if MaxEnt is achieved, there is no need to accumulate further information beyond the information about the macrostates and constraints. Certainly, computational efficiency and speed is also a central criterion in natural selection. That is, we can hypothesize that natural selection manifests the MaxEnt principle in the sense that all processes of observation will follow the MaxEnt logic, which, however, in the context of natural selection also has a direct physical complement in terms of the evolved functions qua physical inference devices.

Frank (2009a,b) has recently presented a strong argument in favour of this view in demonstrating that all statistical distributions observed in nature can be reduced to the MaxEnt formalism (for related arguments, see Grönholm and Annila 2007, or Dewar and

Porté 2008). For example, a power law in the distribution of certain biological phenomena can be explained as the MaxEnt solution in terms of the constraints under which the corresponding process operates. That means, the statistical distributions reflect the information that is necessary for systems functioning in the context of natural selection. Insofar as the natural distributions (of species, of ecological variables etc.) correspond to this statistical pattern, we can directly conclude that evolution follows MaxEnt both formally and materially. In anticipation of the next section, Dewar (2010) has shown that the corresponding MEP principle is an alternative to optimization theories in evolution, i.e. analyzing adaptation (see Grafen 2002, 2007). Whereas optimization theories need to specify certain adaptive functions and construct corresponding measures of performance, the MaxEnt/MEP approach only specifies the fundamental chemical processes (carbon balances, photosynthesis) and the constraints, which in turn depend on the spatio-temporal scale chosen (i.e. the drawing of the system boundaries). In this view, functions can be analyzed on different levels, such as metabolic functions within the plant organism, resulting in the formation of organismic structures and simultaneously maximizing plant respiration, which Dewar regards as the export of entropy. The next higher level combines litter production with plant respiration, and finally, on the ecosystem level, plant and soil respiration combine in producing maximum entropy. The crucial insight is that the adaptiveness of the functions results from evolutionary changes following MEP. Thus, in the evolutionary analysis MEP and MaxEnt converge, because optimization can be both conceived materially (following MEP) and formally (via the connection between optimization, mathematical models of selection, in particular Price's equation, and MaxEnt as demonstrated by Frank).

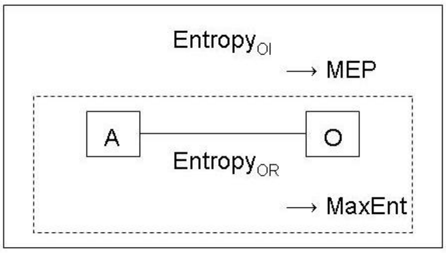
Against the background of these arguments, we can see that the distinction between D-information and SR-information introduced by Ayres (1994) can be resolved in a higher level conceptual synthesis. This is straightforward if we take the same step of naturalizing the observer as in MaxEnt: We can argue that the reference frame for D-information is itself the result of evolution, such that SR-information and D-information are only two sides of the same coin. Indeed, we might argue that SR-information is the observer relative mode, whereas D-information is the observer independent mode of the same underlying physical phenomenon. However, this proposition is only true if we can also give an explication of MaxEnt in terms of the MEP principle, which stands at the center of attention in the current debates over the Maximum Entropy approach..

2.2.2. MEP: The ultimate finality of hierarchical evolutionary systems

The MaxEnt principle does not directly assert that the object system also manifests the state of maximum entropy, but only states that the observing system adopts those representations of the object system in terms of macrostates in which the entropy in terms of the number of possible microstates is maximized, hence the information loss in terms of the proper functioning of the observing system is minimized. The question is, how far does this also imply that the observed system maximizes entropy? This is the hypothesis of Maximum Entropy Production. In asking this question, we switch from $\text{Entropy}_{\text{OR}}$ to observer independent $\text{Entropy}_{\text{OI}}$, because we tacitly suppose that the selection process will approximate a physical reality which is observer independent. This move corresponds to the necessary step in the conceptual foundations of entropy to include always the entire ensemble entropy into entropy analysis, that is, the observed object and the observing system entropy (Zeh 2005: 68ff.). In the argument of section 2.2.1. this means to switch from the function to the entire evolutionary system, into which the observing system is embedded (fig. 4). So, for example, in the Dewar (2010) analysis of plant optimization, we switch between different levels, so that, at the lower level of metabolic organismic functions, the observer relativity of entropy is expressed in the combined affect of plant respiration and structural growth, with the latter being a part of the highest level ecosystem entropy production, combining soil and plant respiration. So, $\text{Entropy}_{\text{OR}}$ (related with Ayres's D-information in the evolutionary view, hence synthesized with SR-information) refers to the plant structure and functions that emerged from natural selection, and $\text{Entropy}_{\text{OI}}$ refers to the total output of the highest level of the evolutionary trajectory.

Fig. 4: Observer independent and observer relative entropy

The analysis of entropy has to distinguish between the causal relation that exists between an observing system O and an observed object system A, and the embedding system that contains the two systems.



Whether the MaxEnt necessarily implies the MEP principle is an open question in the current debate, less theoretically than empirically (Paltridge 2009, Niven 2009; Meysman and Bruers 2010). One argument with direct relevance for the Georgescu-Roegen view is presented in the Earth sciences. This argument is central because it also establishes a direct connection with Lotka's (1922a,b) conjecture about evolution and natural selection, which states that evolving systems maximize energy flux (Kleidon and Lorenz 2005a). Thus, the Maximum Power principle (MPP) is treated as a correlate of the MEP principle. This view has been concisely developed by Kleidon (2009, 2010a) and states that open non-equilibrium systems such as the Earth system will always manifest the tendency to approach the maximum entropy state, which is defined as the macroscopic state which is most probable, given energy and mass-balance constraints. This tendency is empirically complex because the respective manifold processes proceed in vastly different time scales, and correspondingly on different hierarchical levels (Kleidon 2010b). But the general property of these different processes is that they tend towards a solution to the trade off between forces and fluxes that correspond to the MPP, i.e. the point at which the degradation of a force via the flux obtains a maximum value, taking the reduction of the force by the flux into consideration. Kleidon offers the electric circuit model as a conceptual reference structure, which distinguishes between the generators (of disequilibria), the condensators (states far from equilibrium) and resistors (dissipative processes). Every MEP system can then be analyzed as consisting of two loops, with one depleting a capacitor through time via the dissipation of the resistor, and the other adding a current via a generator, which would obtain a steady state away from equilibrium. So, for example, the energy flows in the sun-earth system can be distinguished into the disequilibrium states, i.e the temperature differences (capacitors), the dissipative processes, i.e. emissions of radiation (resistors) and the processes that drive disequilibrium, i.e. absorption of radiation (generators). These are coupled with other subsystems, such as the carbon cycles or the hydrologic cycles. The MEP principle states that all the dissipating structures in these systems will evolve into states in which the gradients of energy dissipation are the steepest, corresponding to the MPP.

Annila and collaborators have recently shown that the maximum entropy approach can be generalized into the analysis of any kind of hierarchical system in which different levels of energy densities prevail, as in the model case of chains of chemical reactions (Annila and Kusimanen 2009, Annila and Salthe 2010). In this case, the probabilities of different microstates can be directly defined via the thermodynamic gradients between the different levels. The MEP principle states that complex systems will always structurally evolve such that over all levels, the rate of energy dissipation, and hence the ultimate production of entropy, will be maximized (for an early version of the gradient hypothesis, see Schneider and Kay 1994).

Lotka’s MPP plays a central role in my philosophical reconstruction of the maximum entropy approach because he argues that thermodynamics has to be supplemented by the principle of natural selection. So, we have a direct correspondence between the role of natural selection in establishing observer relativity in the MaxEnt principle and its role in establishing MEP. His point that natural selection will maximize energy flux (more correctly, in recent terminology, exergy) because this produces performances of living systems that are positively selected by natural selection has been vindicated by many recent generalizations and confirmations (for detailed and encompassing overviews, see Vermeij 2004, Odum 2007). If we relate this with the previous discussion of functions, we have to modify this argument by distinguishing between microscopic and macroscopic aspects of the underlying causalities. In this case, the MPP relates to the macroscopic level, in the sense that maximum power is the state in which the respective functions achieve maximum performances in the macroscopic dimensions. In the same way as the MaxEnt principle states that the approximation to the true macroscopic pattern is achieved via the maximization of the entropy of the microstates, the MEP principle states that the maximum power state is achieved on the macroscopic level if microscopic entropy production of the entire system is at the maximum. This establishes the second evolutionary rationale for the correspondence between MaxEnt and MEP. For example, a species will evolve towards the maximization of macro-level properties such as body size, speed of movement, range of action etc., which at the same time implies that these are gradients in the hierarchical structure of the embedding ecosystem along which energy dissipation is maximal, thus ultimately maximizing entropy$_{OI}$.

It is absolutely necessary to draw the correct system boundaries here, as in the example of plant optimization offered by Dewar (2010): Plant respiration on lower levels, strictly speaking, corresponds to MPP, and MEP drives the entire process of structural ecosystem evolution, such that the corresponding MEP steady state only applies to full extent on this highest level. Similarly, the MEP principle also needs proper reference in time scales (see Vallino 2010) and also implies that the increasing variation of flow channels is another form of entropy production, which would include the existence even of channels working in the opposite direction (Niven 2010); in both cases, what counts is the change of the average entropy production through time within the encompassing system. The proper consideration of system boundaries also helps to conceptualize the role of related approaches which sometimes seem to be alternative views, such as the approach to the thermodynamics of open complex systems which has been proposed by Bejan and dubbed the ‘Constructal Law’ (Bejan and Lorente 2006). It posits that flow systems will always attain states in which the gradients of the dissipation of the flows will be maximal, which corresponds to Lotka’s view, but clearly focuses on the level of structural evolution (the evolution of functions, in my parlance).

It is important to notice that the MPP builds the bridge between MEP and economic applications. This can be shown by analyzing the physical notion of work in terms of the statistical mechanics framework. In thermodynamics, work is defined negatively as all energy transfers between systems that do not directly involve a difference in temperature, hence heat transfers (Gillett 2006: 59). Positively, in the statistical mechanics framework, work is an energy transfer that changes macrostates, with heat being the energy transfer that changes microstates, given constraints. This definition allows for an interesting switch to the everyday notion of work, which relates to the purposive expense of effort. This can be systematically integrated in the evolutionary framework in which we can define work as an energy transfer that affects a function, hence causally relates macrostates of systems. This energy transfer is the depletion of exergy, given the function by which work is realized. This endogeneity of the notion of work in the evolutionary context (see Salthe 2007) is reflected in the contextuality of the fundamental relation between information, exergy and environment in thermodynamics (Ayres 1994: 44ff.). Whereas in more simple physical applications the reference frame can be just defined via the temperature of the environment, the reference frame in case of functions involves structural and morphological features that are much more difficult to determine (Ayres 1994: Chapters 10 and 11). This means, the analytical category of ‘work’ is itself endogenous to evolution, corresponding to the endogeneity of the observer, i.e. the evolving physical inference devices.

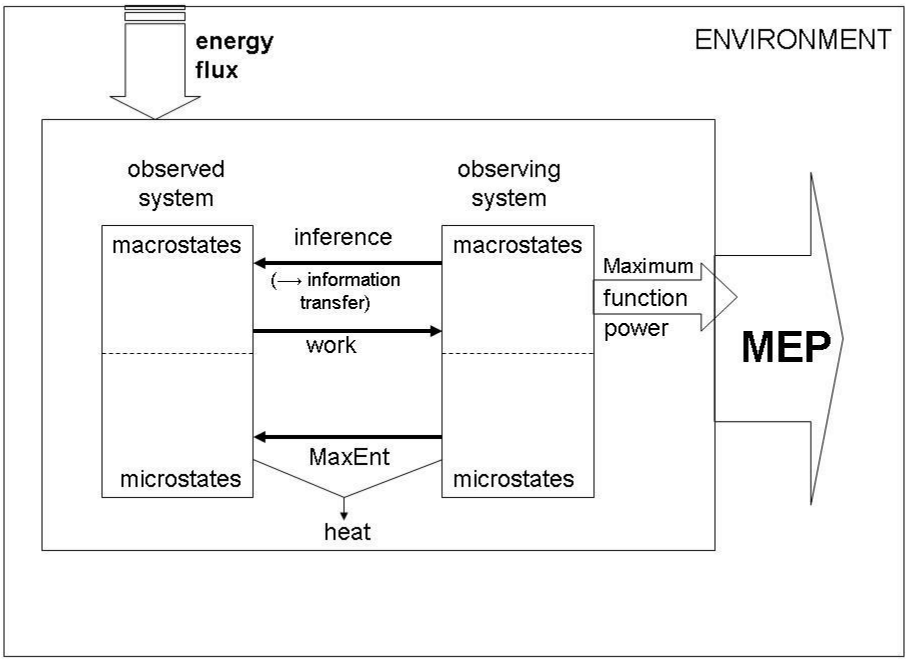
These observations are essential to deal with one important principled criticism of the use of entropy in economics, which has been put forward by Khalil (2004), and which certainly resounds with the opinion of many economists. This is to oppose the analytical level of thermodynamics to the level of human agency. The gist of the argument is to state that the notion of a ‘resource’ is relative to agency, such that there is no standard benchmark for measuring the entropic state of a given endowment with resources. This argument builds theoretically on a confrontation between the statistical mechanics approach to entropy and the classical phenomenological approach, which dominates engineering and refers to the archetypical case of the Carnot cycle. Khalil argues that the standard physical treatment overlooks the entral role of human agency in establishing the Carnot cycle in the first place. In the evolutionary framework outlined so far, this opposition does no longer hold, because human agency is considered as a special case of an evolved function. Thus, the MPP as a principle of natural selection also operates for all extensions such as, in technology, the evolution of artefacts under economic selection, which matches with the existing generalizations of the principle in general ecology (Odum 2007). That means, a steam engine, together with the human agent using it, is just another manifestation of physical inference devices which evolve, for example, in the direction of higher efficiency. Higher efficiency follows MPP in the sense of maximizing work output, but this also implies that ultimately this output dissipates, taking proper system boundaries into consideration. Ultimately, the steam engine is just one way to increase the steepness of the gradient of energy dissipation, and hence, entropy production, in the sense of the MEP principle.

This view also presents the solution to the second major criticism that is put forward by Khalil, namely that the direct transfer of the concept of entropy confuses the micro- and the macrolevels, with the notions of agency, work and resources having no sensible correspondences with the population level concepts of randomness on the microlevel in statistical mechanics. This point loses validity in the MaxEnt view, which uses an observer relative notion of entropy. In this case, we only need a distinction between micro- and macrostates in terms of the implied ignorance on part of the observer, who is able to observe macrostates, but cannot ascertain the corresponding microstates. This corresponds to the differential capacity of systems in extracting work from fundamental thermodynamic fluxes. This is a universal property of all complex evolutionary processes, and thus also applies for the evolution of artefacts such as steam engines: We only have to consider the population of all evolving devices that operate as ‘steam engines’, and to refer to an observer that would have to ascertain all possible physical states of those devices, in relation with their performance evolving through time, relative to certain selective criteria (on the evolutionary approach to technology, see Ziman 2000; on the relation between biological and technological functions, see Krohs and Kroes 2009).

I summarize my argument so far along the structure outlined in figure 5.

Fig. 5: The relationship between MaxEnt and MEP

In a general structure of evolving systems under natural selection, the interaction between observing and observed systems is governed by the MaxEnt principle. The entire system is embedded into the environment via energy throughputs and energy dispersal. Energy *dispersal happens via work and heat, with reference to macroscopic and microscopic processes. The actualization of functions under natural selection follows the Maximum Power principle. As a result, the entire system ultimately realizes MEP.*



The diagram shows an open system that is embedded into the environment, and which is turn consisting of two systems which stand in the causal relation of observation with each other. This is the most simple form of a hierarchical structure. The observing system manifests a function with reference to the higher-level system, such as an adaptation in an ecosystem. Then, the conjoint hypotheses of MaxEnt and MEP imply:

1. The higher level system receives an energy flux which is dissipated via the causal processes of the lower-level systems on both the macroscopic and the microscopic level.
2. The lower-level observing system relates causally with the object system, such that the observed system transfers energy to the former in the form of work, which involves conjoint changes of macrostates. This change of macrostates of the observing system contributes to the realization of a function.
3. The observing system infers the macrostates of the observed system via the MaxEnt process, which implies maximization of entropy$_{OR}$ with reference to the microstates.
4. Both systems dissipate energy on the microscopic level in the form of heat, concomitant with the macroscopic causal interaction.
5. The function of the observing system maximizes power as a result of the natural selection of functions.
6. The entire, hierarchically nested and causally coupled process maximizes entropy$_{OI}$.

The distinction between Entropy$_{OI}$ and Entropy$_{OR}$ is essential for this view. The MEP does not simply state that entropy$_{OI}$ is maximized, even though this is the final result of all processes that take place e.g. in the earth system. If so, all processes would just explode into heat. However, this is physically impossible, given the constraints of physical laws. Hence, systems evolve into more complex structures in which energy is dissipated in the most rapid and efficacious way, given the constraints. In order to analyze this process, entropy$_{OR}$ is the relevant category. If we argue in the entropy$_{OR}$ context, the concepts of work, power and exergy are relevant, If we argue in the entropy$_{OI}$ context, the concepts of energy and heat are relevant. The two levels are conjoined in the maximum entropy principles. These principles imply a specific relation between observer independence and observer relativity. As we have seen, observer relativity inheres the identification of the constraints under which a system operates, relative to a function. This is why a category such as work both involves the reference to macroscopic levels and to notions of purposiveness. Observer independence inheres the ultimate criterion of entropy maximization.

Fig. 6: The relation between the central laws and hypotheses of the Maximum Entropy approach

The Second Law and Natural Selection are the two fundamental hypotheses. The Second Law is the foundation for the MEP principle. The natural selection of functions establishes the differentiation between observer independent and observer relative entropy. On the macroscopic level, the MEP principle is expressed in the Maximum Power principle which relates to functions. The MaxEnt principle relates the macroscopic with the microscopic level.

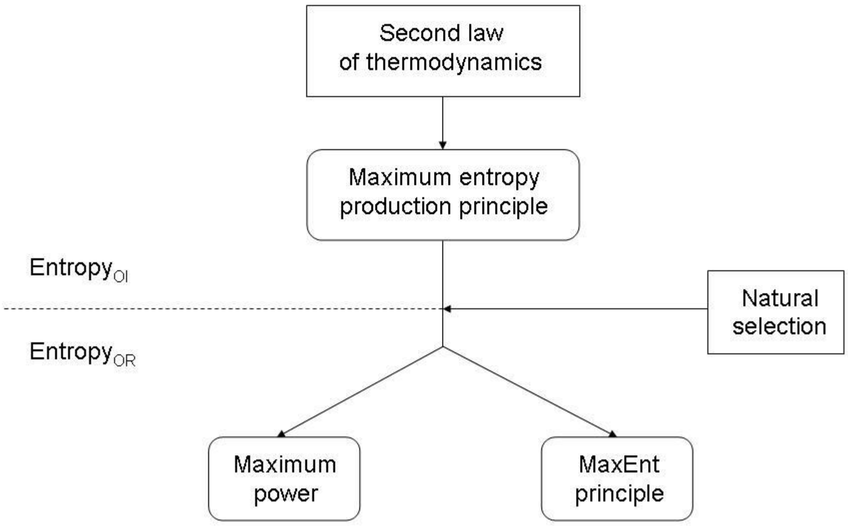


Figure 6 summarizes the relationship between the fundamental laws and principles of the Maximum Entropy approach, as applied in the context of evolution.

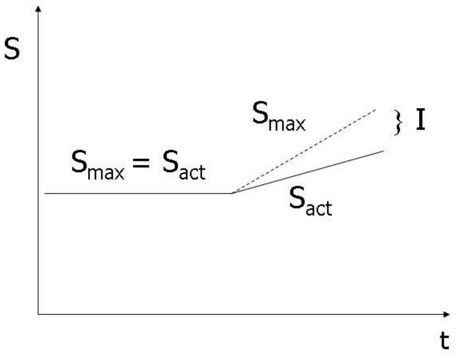
3. The broader ontological setting and the problem of time

I will now relate the results of section 2 with Georgescu-Roegen's two notions of time. This is straightforward in just applying a conceptual parallelism in the first place. In the previous section, I have substituted Jaynes's notion of subjectivity with the generalized notion of observer relativity. Now I equate Georgescu-Roegen's notion of subjective time with observer relative time, and his notion of mechanical time with observer independent time. This has a consequence which certainly transcends his own views, which very much emphasize the mental side of 'subjectivistic time' but which also renders his conceptual connection between time and evolution more precise. Then, subjectivistic time would appear as time relative to an evolutionary process, in which the changing structure of functions and hence the structure of the space of possible states generates the yardstick against which the directedness of the entropic flows can be asserted. As a reminder, one fundamental problem in thermodynamics is the relation between the statistical mechanics notion of probability and the macroscopic notion of irreversibility which frequently has been declared to be the anchor of the arrow of time inhering the Second Law (Sklar 2009). However, as Uffink's (2001) painstaking analysis has shown, standard thermodynamics, both in the phenomenological and statistical mechanics version, does not offer a clear and unequivocal account of time. This is certainly true for the MaxEnt approach, which has no ontological implications whatsoever, and in this regard reflects the timeless features of the Gibbsian equilibrium notions. In this context, Georgescu-Roegen seems to offer an alternative, if we transform his subjectivistic view into the notion of time which is endogenous to evolution. A solution to the quandary can be found in expanding into the broader systematic conceptual frame firstly proposed by Layzer (1988) and later developed in more detail by Chaisson (2001, 2005), with another application in biology in the theories proposed by Brooks and Wiley (1988) and Salthe (1993).

The central concept in the statistical mechanics approach is that of the state space. Layzer introduced the distinction between potential, i.e. maximum entropy and actual entropy, which allows to analyze the case of an increasing state space, which is the regular situation in an expanding universe (for a critical view on this, see Lineweaver 2005; compare the discussion in Penrose 2006: 696ff., or Callender 2009). From this follows that in an expanding state space, accumulation of information is possible as long as there is a increasing gap between potential and actual entropy (see figure 7).

Figure 7: Divergent evolution of potential and actual entropy

In the initial state of cosmic evolution, all potential entropy was actual. With the expansion of the universe, the gap between potential and actual increases, because of the constraints on the physical mechanisms in realizing potential states of the world.



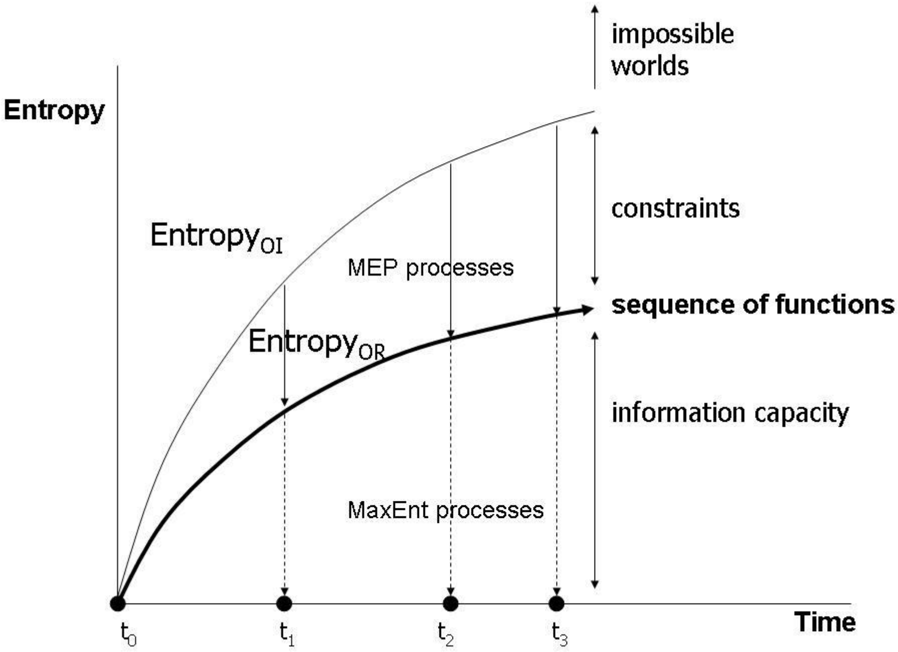
This shows that the emergence of life and of highly complex systems actually follows the Second Law, because it feeds on the increasing information capacity generated by actual entropy, but at the same time maximizes entropy because of the increasing gap to potential entropy. This corresponds to the idea that all systems ultimately are mechanisms for energy dissipation, and hence do not work against the Second Law. We can give a more general version of this idea in terms of a general evolutionary law of increasing information content of realized systems. This law can be directly deduced from Weitzman's (1998) conception of combinational growth in evolution. We only need to assume that evolution proceeds in the way that existing potential states of systems are continuously combined into new possible states, such that, mathematically, the power set of all possible combinations grows when the underlying states space grows. From this follows the Weitzman proposition that all recombinant processes grow stronger than exponential growth processes, which implies that realized forms of life represent an increasing information content because of the growing distance between the realized states and the possible states.

Following Layzer, Brooks and Wiley (1988) have proposed a simple qualitative diagram that I adapt here (fig. 8). The central message of this diagram is that the evolution of functions qua physical inference devices can be seen from two sides, namely entropy$_{OR}$ and entropy$_{OI}$. The evolution of functions maximizes entropy$_{OR}$ in the sense that on every step of functional evolution, the system of functions of observing systems will manifest the MaxEnt principle.

Hence, we have different points in time onto which the state of entropy_{OR} is projected. However, these different points are incommensurable in the Georgescu Roegen sense because the underlying dynamics follows the Weitzman growth trajectory, i.e. manifests structural novelty in the possible combinations of states. Therefore, for each point of time the MaxEnt principle holds, but it is impossible to compare the different entropies even qualitatively. This is exactly on what both Jaynes and Georgescu-Roegen could agree, though from a very different, even seemingly incompatible standpoint. In other words, and referring again to Ayres' distinction between D-information and SR-information, the D-information in every point is contextualized with reference to the realized function, such that no unified measure exists, even though the fundamental physical processes follow the same laws.

Fig. 8: The evolution of entropy (adapted after Brooks and Wiley 1988)

The purely qualitative diagram shows the two-sidedness of functions in evolutionary sequences that are projected onto physical time. Ultimately, functions dissipate energy and hence drive the growth of observer independent entropy. At the same time, they maximize observer relative entropy in the process of selection. The latter creates the information capacity from which new functions can emerge, thus driving further qualitative changes of the state space. Across the different points of time, Entropy_{OI} *is commensurable, and* Entropy_{OR} *is incommensurable, corresponding to Georgescu-Roegen's two conceptions of time.*



However, the process also manifests continuous growth of entropy_{OI}, which is the reflection of the direct physical complementarity of the statistical mechanics and the thermodynamic view on entropy. As I have detailed in figure 5, this reflects the fact that via the working of functions, energy is dissipated corresponding to the MPP, which, together with the dissipation into useless heat along the different levels of hierarchical systems with functions, ultimately results into MEP on the level of the total system. This approach is different from the Schrödinger view on evolution because all functions are seen as MEP gradients. The Schrödinger view that organism are states of order implicitly assumes a stable reference frame. However, in a moving reference frame the definition of order is endogenous. This is familiar from biology, where we can speak of entropy, in the sense of diversity, on different hierarchical levels, such as the diversity of individuals within a species, are the diversity of species in an ecosystem, and so forth. From the viewpoint of the individual diversity, the species characteristics may appear to be states of order, but they are themselves entropic phenomena on a higher level.

Hence, fig. 8 represents the essence of my reconciliation between Georgescu-Roegen's fundamental philosophical position and modern Maximum Entropy approaches. Georgescu-Roegen's central concern was to distinguish two kinds of theories, arithmomorphic and qualitative (dialectic). The essence of this distinction lies in two different notions of time. In fig. 7 we have the mechanical time still on the x-axis, but there is a twofold projection. Whereas entropy$_{OI}$ corresponds to the arithmomorphic framework of statistical mechanics and thermodynamics, which was rejected by Georgescu-Roegen, it is precisely the modern approach to entropy developed by Jaynes that allows to recognize the role of Entropy$_{OR}$. Entropy$_{OR}$ is a dialectic category that evolves endogenously with the qualitative evolution of the state space, hence the reference frame. It is only in this mode we can speak of an arrow of time. Georgescu-Roegen was right in questioning the possibility of an arrow of time in the purely physical context (compare Barbour 1999; Callender 2009). He was also right in seeing time as an essential category in understanding evolution. But in my view, the reference point for time is not the flow of consciousness, but evolution itself, of which the flow of consciousness is only one expression.

4. Conclusion: The relevance of the argument for economic analysis

I have shown that a fundamental feature of Georgescu-Roegen's natural philosophy of economics, namely the dualism of notions of time, can be interpreted in the context of modern maximum entropy approaches. The bridge is built on a generalization of Georgescu-Roegen's reference to subjectivity, which I interpret as observer relativity, and in a second step of extension, as function relativity in an evolutionary context. I argue that the MaxEnt principle applies for the evolution of physical inference devices under natural selection, because it represents a principle of economics of information. MaxEnt implies the adaptation of functions to macro-level constraints, with no loss of information from imperfect information about the microstates. In evolutionary hierarchical systems, this corresponds to the MEP principle, because natural selection, following Lotka's seminal conjecture, manifests the MPP in terms of the functions. In this sense, the treatment of time is just a capstone completing the general Maximum Entropy framework in terms of re-instating Georgescu-Roegen's natural philosophy, in which entropy production is the core notion.

The Maximum Entropy approach presents the conceptual and philosophical framework for recent work by Ayres and collaborators (Ayres 2005, Ayres et al. 2005, 2008, Warr et al. 2008), in the same direction as e.g. Kümmel (1998), which shows that economic growth can be explained by the growth of useful work throughput, once the technological improvements in the transformation of exergy into work are taken into consideration. This is because exergy is the context-specific amount of free energy available in the system environment, and work is the useful energy expended in changing macrostates of systems. I interpret the effective substitution of the technological progress variable by the useful work variable in these models as a direct correspondence to the dualism between entropy$_{OI}$ and entropy$_{OR}$.

Economic growth directly reflects the Second Law in both senses, thus re-instating the original Georgescu-Roegen position. Firstly, economic growth is a sequence of functions which define a sequence of Entropy$_{OR}$. This is what reflects the increasing quantity of information that underlies the growth trajectory, and is the result of economic selection of functions, i.e. technologies, institutions etc., which are manifestations of physical inference devices in the context of human culture Secondly, economic growth manifests the continuous increase of energy throughput, hence the growth of Entropy$_{OI}$. This is reflected in the so-called rebounce effect, namely that in spite of ongoing technological innovation, the exergy throughput increases continuously (Ayres et al. 2003, 2005). This implies that we can interpret the increasing efficiency of the exergy/work relation as a movement towards steeper gradients in energetic dissipation, following MPP. In other words, increasing energetic efficiency of technology does not result into absolute savings of energy, but actually supports increasing use of energy, corresponding to the ultimate MEP principle. Recently, Garrett (2009) proposed a very simple thermodynamic framework that grasps these essentials: The human economy is treated as a heat engine, which is driven by an energy potential created at the interface between the economy and its environment. This system produces work and heat. Garrett then introduces a direct feedback mechanism between work and the changes of the energy potential, which implies continuous growth, fed by energy throughputs and changes in the efficiency of the heat engine, the latter defining a rate of return in physical terms (which he can also relate with economic magnitudes in the full elaboration of the model). This model directly generates the rebounce effect, and the changes in efficiency can be equated with the evolution of information in my sense, i.e. the role of physical inference devices. Interestingly, and exactly matching with the philosophical perspective proposed in this paper, 'work' emerges as a 'subjective' magnitude, and especially, it is relative to the system boundary and, hence, the energy potential defined at this boundary. This grasps the role of endogenous evolutionary forces, including human agency in the Khalil (2004) sense, in driving the thermodynamics of the system, but it does not change the direction of the flows, which corresponds to the Second Law.

This statement means, as Annila and Salthe (2009) have argued recently, that we can assume for economic growth a similar process as for the general case of the Earth system. This is that all economic institutions, technologies etc. at least in the average will change in the direction of establishing gradients for energy dissipation that maximize entropy production. This, however, and contrary to Georgescu-Roegen, should not be directly interpreted in the sense of environmental issues, because the dissipative process can take many different forms, some environmentally degradating, others not, depending on the specific functions that underly the gradients. Further, the central input driving the evolution is exergy, but not any sort of 'low entropy' stored in material resources (thus agreeing with Gillett 2006, in principle). However, it does imply, and here corresponding to Lotka's conjecture, that economic evolution is always and necessarily accompanied by increasing energy throughputs and maximal entropy production (thus, and contrary to Gillett 2006, agreeing with Lozada 2006). The MaxEnt/MEP framework implies that economic evolution always works in the direction of increasing the gradients of energy dissipation via emergent structural properties, which I have generically called 'physical inference devices', referring to technology and institutions in the economic context, in particular.

This observation may be too obvious, but in fact it is not, given the implicit belief shared among many economists that the growth of knowledge itself may be a substitute for the use of energy. The other central consequence of the maximum entropy framework is that one cannot treat information as an entropically irrelevant magnitude. This is evident to the physicist or ecological economist, but is rarely recognized in standard economics, where information is normally treated in mentalistic terms, as in the classical notion of exogenous technological change, or in the entire domain of game theory. The argument presented here implies that information always has two sides, the OI side and the OR side. Economics only focuses on the latter and ignores the former. The former has been recognized since Landauer (1961) as the energetic and entropic equivalents of Shannon information in computation as a physical process (for an overview, see Maroney 2009). In the context of economics, this implies that one cannot simply think of information as a generic resource that can substitute for energy, as Kümmel (1998) has suggested, and is the implicit assumption in neoclassical environmental economics. Energy and information are two sides of the same coin, and the difference is only a structural one, relating to the functions. That means, intensifying information flows and information use will always follow the Second Law. Therefore, we can hypothesize that the growth of energy throughput and hence, entropy production, is the dual of the growth of knowledge. In this sense, Georgescu-Roegen's warning voice is still with us. There is no escape to the entropy law.

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