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Entropy

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1. Introduction

All processes of macroscopic change are irreversible. Examples include natural processes, such as the growing and blooming of a flower, as well as technical processes, such as the burning of fossil fuels in combustion engines. The entropy concept has been coined in thermodynamics to capture this fact of nature. At the same time it allows to make quantitative statements about the efficiency of energetic and material transformations. Its origins are in the 19th century when practitioners, engineers and scientists like James Watt (1736-1819), Sadi Carnot (1796-1832), James Prescott Joule (1818-1889), Rudolph Clausius (1822-1888) and William Thomson (the later Lord Kelvin, 1824-1907) wanted to understand and increase the efficiency at which steam engines perform useful mechanical work. By now, the original notion of entropy has been greatly generalized and applied in many different contexts outside classical thermodynamics. There exist a number of alternative definitions of the term, not all of them formally consistent with each other. Because the entropy concept is multifarious, it is also complex and difficult to understand.

2. What is entropy?

The nature of the thermodynamic entropy concept can be grasped from an analysis of the so-called Carnot cycle, an idealized model of a heat engine which performs mechanical work through the flow of heat from a hot reservoir at temperature T_h to a reservoir at lower temperature T_l. The maximum efficiency of such a heat engine is $1-T_\mathrm{l}/T_\mathrm{h}$. The larger the temperature difference between the hot and the cold reservoirs, the larger is the fraction of heat that can possibly be converted into work. Clausius defined a variable S by $\mathrm{d}S=\mathrm{d}Q/T$, where $\mathrm{d}Q$ is the amount of heat transferred to or from the system in a reversible way at temperature T. He called it *entropy*, based on the greek τροπη, which means transformation, by analogy with the name ‘energy’. Clausius showed that entropy is an extensive state variable of the system. This means, it is proportional to the size of the system and at any time only depends on the state of the system. He also proved the epochal result that it remains constant in any reversible cycle and increases during an irreversible cycle.

The *Second Law of Thermodynamics*, the so-called Entropy Law, uses the entropy concept to express the everyday experience that transformations of energy and matter are unidirectional. It states that the entropy of an isolated thermodynamic system never decreases, but strictly increases in irreversible transformations and remains constant in reversible transformations. This places significant constraints on natural as well as technical processes. For example, the temperature of a cup of hot coffee left in a cold room will always decrease, never increase, to eventually reach equilibrium with room temperature. In this process, the entropy of the room has increased. Thus, the entropy concept allows to define an ‘arrow of time’.

While the original notion of entropy is based on heat, Ludwig Boltzmann (1844-1906) introduced a notion of entropy that is based on statistical mechanics and likelihood. Formally, one can define the entropy of a probability distribution of a set of mutually exclusive events i as $S = - k \sum p_i \log p_i$, where p_i is the probability that event i occurs, k is a factor of proportionality (now called Boltzmann's constant) and the sum is over all possible events. Boltzmann took the event i to be that a thermodynamic system is in microstate i, compatible with its observed macrostate. He posited that all microstates have equal a priori probability and introduced the quantity Ω as the number of microstates of a system compatible with its observed macrostate. Then $S = k \log \Omega$. Boltzmann’s entropy is a measure of both microscopic disorder and macroscopic likelihood: high entropy characterizes a macrostate which is highly probable, since it can be realized by a large number of microstates in which the individual constituents are arranged in a spatially even and homogeneous way (‘mixed-up systems’). The irreversibility stated by the Second Law appears as the statement that any isolated macroscopic system always evolves from a less probable (more orderly) to a more probable (less orderly and more mixed-up) state, where Ω and S are larger.

Boltzmann’s statistical entropy notion later has been transferred into mathematical statistics and information theory. As a general measure of evenness and homogeneity it is used to construct indices for the measurement of all kinds of heterogeneity in natural and social systems, for example income inequality, industry concentration, or biodiversity. Although the name ‘entropy’ is usually retained in these contexts it is used as a purely statistical device and does not have any substantial relation with the thermodynamic entropy notion which refers to energetic and material transformations.

3. How is entropy relevant for Ecological Economics?

In the analysis of economy-environment interactions, e.g. resource extraction, energy use, production, and generation of wastes, the entropy concept is most useful in its thermodynamic version. It can be applied to both microeconomic as well as macroeconomic processes.

Thermodynamic entropy is a measure of the (in)ability of a system’s energy to perform work. As the entropy of an isolated system increases, its *available energy* (also called *available work* or *exergy*) decreases. Available energy corresponds to the useful part of energy, which can be transformed into work. It thus combines the insights from both the First Law of Thermodynamics (conservation of energy) and the Second Law of Thermodynamics (generation of entropy). Available energy is what most people mean when they use the term ‘energy’ carelessly, e.g. when saying that ‘energy is used’ to carry out a certain process. The Entropy Law thus states that with every transformation an isolated system loses part of its ability to perform useful mechanical work. As the system approaches thermodynamic equilibrium over time its entropy will increase until it reaches a maximal value. In this final state of maximum entropy, the system’s potential for work is zero. In as far as the universe as a whole can be described as an isolated system, its final state is such a state of maximum entropy and zero potential for work – a state described as ‘heat death’. The evolution of an isolated system towards maximal entropy defines the so-called first arrow of time as an expression of irreversibility in isolated systems.

Nicholas Georgescu-Roegen (1906-1994) was the first economist to realize that the Entropy Law imposes limits on the economic process. He considered it ‘the most economic of all physical laws.’ His seminal work gave rise to a vast strand of fruitful research. But his postulate of a so-called ‘Fourth Law of Thermodynamics’, which cannot be justified on thermodynamics ground, also initiated a heated (and still ongoing) debate, in which the economic relevance of the Entropy Law was sometimes dismissed altogether. In thermodynamic view, the economy uses low entropy energy and matter from its surrounding natural environment, to produce consumption goods, and discards high entropy wastes back into the environment. Georgescu-Roegen saw the Entropy Law as a metaphor for the inevitable decline of such a system, where every act of production and consumption brings the economy closer to doomsday in the form of ‘heat death’.

But, of course, neither the economy nor Planet Earth at large are isolated systems. Whereas the Second Law makes a statement about isolated systems in thermodynamic equilibrium only, entropy is a meaningful and useful variable in open systems near and far from equilibrium, too. Any open system is a subsystem of a larger and isolated system. According to the Second Law the entropy of the larger and isolated system has to increase over time, but the entropy of any open subsystem can, of course, decrease. This is achieved by export of entropy from the subsystem to its surrounding through flows of energy and matter. Viewing open systems as subsystems of larger and isolated systems reveals that an entropy decrease in an open subsystem necessarily has to be accompanied by an entropy increase in the system’s environment, that is the rest of the larger, isolated system, such that the entropy of the total system increases. Open subsystems can maintain an ordered state or even increase their order on the expense of the entropy of their surrounding increasing. The build-up of order in a self organised-way by the dissipation of energy far from thermodynamic equilibrium also constitutes an arrow of time. It is an expression of time irreversibility as it is manifest in open systems far from equilibrium.

Every living organism is an example of such an open system. As Erwin Schrödinger (1887-1961) put it: ‘Life feeds on low entropy.’ Similarly, production can be seen as a transformation process within an open economic system, whose purpose it is to increase order, e.g. the purification and reduction of oxide metal ores into pure metal. Planet Earth is also an open subsystem, as it receives low entropy energy from the sun and radiates high entropy in the form of low temperature heat back into space. Georgescu-Roegen’s view that any economic action inevitably increases the Earth’s entropy and brings it closer to its ultimate fate of a heat death may thus be considered too pessimistic. On the other hand, it becomes apparent that the ultimately limiting factor is the rate of low entropy energy influx from the sun and the rate of high entropy energy export into space.

4. Conclusion

All taken together, the entropy concept is relevant for Ecological Economics in various ways and on different levels of abstraction. First, as all processes of change are, at bottom, processes of energy and material transformation the entropy concept applies to all of them. It thus creates a unifying perspective on ecology, the physical environment, and the economy. It allows to ask questions that would not have been asked from the perspective of one scientific discipline alone. Second, on a more specific level the concept allows to incorporate physical driving forces and constraints in models of economy-environment interactions, both microeconomic and macroeconomic. It is essential for understanding to what extent resource and energy scarcity, nature's capacity to assimilate human wastes and pollutants, as well as the irreversibility of transformation processes, constrain economic action. The entropy concept thus allows economics to relate to its biophysical basis, and yields insights about that relation which are not available otherwise. Third, on an even more applied level the entropy concept provides a tool of quantitative analysis of energetic and material transformations for engineers and managers. It may be used to design industrial production plants or individual components of those such as to maximize their energetic efficiency, and to minimize their environmental impact.

With its rigorous but multifarious character as an analytical tool, its rich set of fruitful applications, and its obvious potential to establish relations between the natural world and purposeful human action, the entropy concept is one of the cornerstones of Ecological Economics.

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Online references:

Concise explanations of the technical terms and concepts used here can be found in Xrefer, a site that contains encyclopedias and dictionaries from the world's leading publishers.

The entry on thermodynamics in the Information Please-Encyclopedia discusses the role of entropy and the entropy law in the broader context of thermodynamics.

The Page of Entropy offers a nice and non-technical introduction to the statistical notion of entropy.

Two sites that give a more casual introduction to the intuition and real world experience of the entropy law are The Second Law of Thermodynamics and Entropy and the Second Law of Thermodynamics. Focus on chemistry and chemical reactions.

Entropy on the WorldWideWeb offers information on the use of the entropy concept in different academic disciplines and links to relevant journals, conferences, research groups and software. Focus on information theory.

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